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Statistical Acceptance Plan for Asphalt Pavement Construction

by Reed B. Freeman, William P. Grogan

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Waterways Experiment Station
3909 Halls Ferry Road
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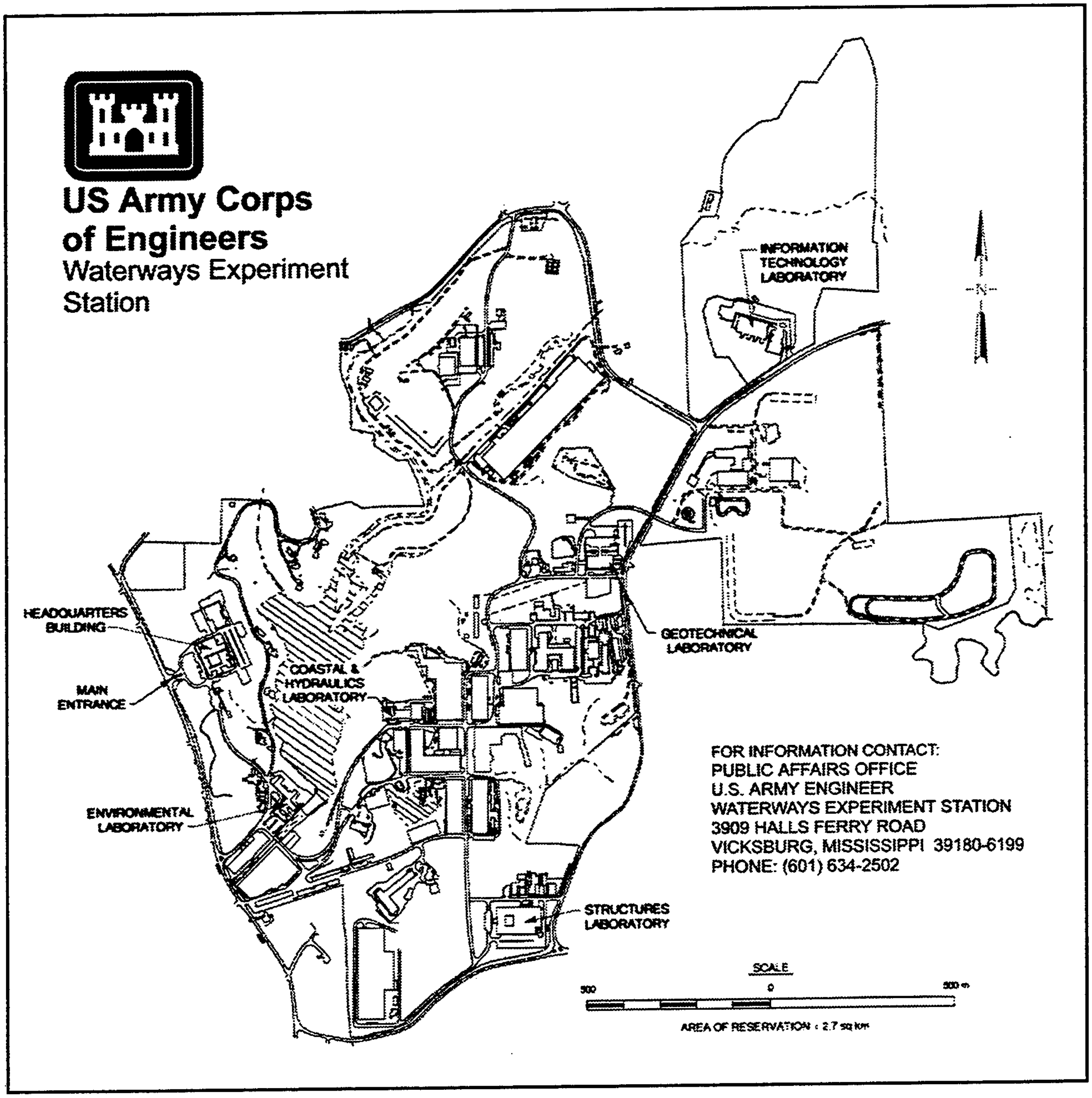

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Preface

The investigation documented in this report was sponsored by the U.S. Army Corps of Engineers through the Research, Development, Testing, and Evaluation (RDT&E) Program, Technology Work Package, Work Unit AT40-PT-14, "Statistical-Based Pay Adjustment Factors for AC Pavements." The Corps of Engineers Technical Monitor was Mr. Ray Navidi, CEMP-ET.

This research was conducted by personnel of the Airfields and Pavements Division (APD), Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS.

This study was conducted under the general supervision of Dr. William F. Marcuson III, Director, GL. Direct supervision was provided by Dr. David W. Pittman, Chief, APD, and Mr. Timothy W. Vollor, Chief, Materials Analysis Branch (MAB), APD. The principal investigator for the project was Dr. Reed B. Freeman, MAB. The report was authored by Dr. Freeman and Mr. William P. Grogan, MAB.

Director of WES during the conduct of this study and preparation of the report was Dr. Robert W. Whalin. The Commander was COL Robin R. Cababa, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet (cu ft)	0.02832	cubic meters (m^3)
feet (ft)	0.3048	meters (m)
gallons (gal)	3.785	liters (L)
gallons per square yard (gsy)	4.5273149	liters per square meter (L/m^2)
inches (in.)	0.0254	meters (m)
kips (1,000 lb)	0.4535924	1,000 kilograms (1,000 kg)
pounds (mass) (lb)	0.4535924	kilograms (kg)
pounds (force) per square inch (psi)	6.894757×10^{-3}	megapascals (Mpa)
pounds (mass) per cubic foot (pcf)	0.157	kilonewtons per cubic meter (kN/m^3)
square inches (sq in.)	6.4516×10^{-4}	square meters (m^2)
square yards (sq yd)	0.8361	square meters (m^2)

1 Introduction

Prior to 1970, pavements were typically constructed with "materials and methods" specifications, through which the contractor was directed to use specific materials in definite proportions and to use specific types of equipment under a specific mode of operation. Experience has shown that this type of contract obligates the owning agency to accept the completed work.

Currently, many agencies involved with the construction of pavements are implementing end-result specifications, through which the contractor is required to take responsibility for supplying a product or an item of construction. The owning agency either accepts or rejects the final product or applies an adjustment to the contract price. The monetary adjustment accounts for the degree to which the final product complies with specifications. End-result specifications shift some responsibility to the contractor, but they also provide the contractor with some decision-making power. The contractor has freedom to use new materials, techniques, and procedures to improve the quality and/or economy of the final product (TRB 1996).

The development of end-result specifications require logical relations between expected pavement performance and the material characteristics that are measured to judge contractor performance. The measured material characteristics and any additional construction quality parameters used in these specifications must have previously been found to correlate with fundamental engineering properties that affect pavement performance. Examples of these characteristics include the air void content of asphalt concrete and the compressive strength of portland cement concrete (TRB 1996).

Decisions concerning contractor performance are based on information obtained from random samples. The act of making judgements about a product, based on sample statistics, imposes risks for the contractual parties. The risks are associated with the accuracy of conclusions based on finite information (small samples). The development of performance-related, end-result specifications requires the use of statistical concepts so that each contractual party assumes a fair share of risk. Theories of probability and statistics permit engineers to account for and control uncertainties associated with sampling.

Background

The American Association of State Highway Officials (AASHTO) Road Test was constructed in Ottawa, Illinois in 1959 to evaluate the design and construction practices for asphalt and portland cement concrete roadway systems. Prior to this effort, highway engineers were aware of the inherent material and process variabilities of construction materials. However, during the construction of this test road, highway engineers realized that these variabilities were not being handled properly in specifications. Construction data indicated that even with well-trained inspectors, well-equipped testing laboratories, a competent contractor, and an intensive effort on the part of the road test officials, it was still not possible to entirely meet the specifications that had been prepared. For embankment construction, approximately 83 percent of the field moisture contents were within specifications and approximately 80 percent of the field densities were within specifications. Approximately 64 percent of the asphalt concrete mixtures had binder percentages within specifications. Approximately 91 percent of the asphalt concrete mixtures had total air voids within specifications (Moulthrop 1974).

The construction specifications used for the AASHTO Road Test included both material and method components for its quality requirements. The specified limits for quality characteristics were based on judgment and experience. The development of these tolerances seldom explicitly accounted for the inherent (unavoidable) variabilities of the construction process or the materials.

Typical quality assurance procedures for pavement construction, at the time of the AASHTO Road Test, consisted of periodically taking a single material sample. If the test result was within the stated tolerances, the material passed and was accepted. If the test result was not within the stated tolerances, the material failed to pass. Engineering judgment would then have to be applied for the decision as to whether the material should be retested or whether it could be considered to be in substantial compliance. Substantial compliance meant that the material was accepted because the deviation from specified requirements was not considered to impair pavement performance severely. This practice was difficult to define in legal or contractual terms. Substantial compliance was typically not defined and the degree of acceptable variation differed from engineer to engineer and from job to job (McMahon and Halstead 1969).

As the United States Interstate program moved into its full construction phase, improvements in specification methods became necessary. In 1963, the Public Roads Director of Research and Development appointed a task force to study the problem and develop a cooperative State-Public Roads research effort to improve quality assurance methods in highway construction (McMahon and Halstead 1969). Many of the statistical concepts presented in this report have been applied to highway construction through the efforts of this task force.

Advantages of Statistical Specifications

Statistical specifications have been and are being used by many industries other than highway construction. Since the 1920's, statistical techniques have proven valuable in the chemical, pharmaceutical, goods processing, electronics, steel, textile, packaging, aircraft and automobile industries. Although some of the concepts and statistical techniques from these other industries may not be usable in highway construction, they all deal with a vital common fact: products vary and a knowledge of their variability is essential for accomplishing the most efficient manufacture and use of the products (Dillard 1966).

The application of statistical concepts to highway construction specifications allows a definite assignment of responsibility for product quality. The contractor is strictly responsible for providing quality materials and construction; the owner has the prerogative of acceptance sampling and testing (McMahon and Halstead 1969). The contractor will also have a clearer idea of what final product is required (Baker 1966, Benson 1966). Clear definitions of party responsibilities and product requirements should reduce the likelihood of contractual disputes (Weed 1982). Although contractors rarely accept rejection notices without challenge, they accept rejection more readily when the contract clearly states requirements and clearly describes the procedure used to calculate the level of contract conformance. A contractor will generally trust sound statistical procedures more than an inspector's judgment (Foster and Stander 1966).

By recognizing both inherent and testing variability and by clearly defining acceptance criteria and random sampling procedures, the risks to both contractual parties can be controlled and known in advance (Weed 1982). In addition, decisions can be made with an established degree of confidence. The degree of confidence required for each decision should be a function of how critical the decision is to the quality of the end product (McMahon and Halstead 1969).

In addition to statistical acceptance procedures, the use of statistical process control procedures provides contractors with a method for ensuring that they are meeting necessary requirements. Formal documentation of process control and the maintenance of these records by transportation agencies would facilitate the development of knowledge related to infrastructure material variabilities. Thus, a true perception of what can be achieved practically is acquired, which in turn will lead to more realistic specifications (Foster and Stander 1966). The designer will also obtain an improved knowledge of the materials which will ultimately comprise his structures (Baker 1966).

Obstacles for Implementation

There are several reasons for the highway construction industry's delay in implementing statistical specifications. First of all, defining quality for completed pavements is difficult. In order to implement an end-result type specification that includes statistical concepts, the transportation agency must be able

to specify characteristics of the final product in terms of measurable parameters. These measurable parameters must be related to the quality of service provided by the completed pavement structure (Granley 1969, McMahon and Halstead 1969).

The nature of responsibilities in typical highway construction contracts has also delayed the adoption of statistical procedures (Foster and Stander 1966). State highway departments have historically performed both the process control testing and the acceptance testing. The contractor usually did not perform any testing. This was contrary to most industries where the manufacturer was at least responsible for the process control testing of the product. As a contractual party that performed all quality testing, some transportation agencies were in a difficult position for rejecting any unsatisfactory pavement. They were therefore not anxious to complicate procedures with elements such as pay adjustment factors.

In order to implement statistical end-result specifications for highway construction, contractors must take over process control testing. Consequently, contractors need to implement personnel and equipment changes; they need trained inspectors and technicians and they need sampling and testing equipment. Contractors may need the services of professional engineers trained in process control to lay out sampling and testing programs that will ensure a high percentage of acceptance with the least testing cost (McMahon and Halstead 1969). Due to the costs that accompany process control responsibilities, related transitions in contractual policies should occur gradually (Foster and Stander 1966).

Finally, in order to implement statistical specifications, all contract parties need to become familiar with some statistical terms, such as "standard deviation" and "confidence limits." Generally, learning has not been considered a problem due to the monetary incentives involved (Foster and Stander 1966).

Scope of Report

This report consists of two broad components: a technical review of statistical specifications and the application of statistical concepts to the Corps of Engineers guide specification for heavy-duty hot-mix asphalt pavements. The technical review begins with an overview of the elements that comprise statistical specifications. Then selected basic probability distributions, which are necessary for understanding statistical specifications, are reviewed. Methods are described for developing statistical acceptance plans, for both attributes and continuous variables.

A review of current specifications for hot-mix asphalt pavements, including those used by the Federal Highway Administration, the Federal Aviation Administration, and the U.S. Army Corps of Engineers, is presented. Then a statistical acceptance plan is recommended as a modification for the Corps of Engineers Guide Specification CEGS 02556, "Asphaltic Bituminous

Heavy-Duty Pavement (Central-Plant Hot Mix)" (USACE 1991). In addition to a description of its development, the recommendation is provided in the form of an Engineering Technical Letter in Appendix D. The recommendations provide for the application of statistical concepts without any abrupt changes to either the measured material characteristics or the sampling procedures.

This report does not include recommendations for developing or implementing statistical process control procedures. This is an important element of the specification, which should be addressed in another study. This report also does not address the changes in specifications for hot-mix asphalt concrete that are certain to occur as a result of the recent Strategic Highway Research Program (NAS 1995). However, the statistical acceptance procedures for current specification criteria are described in detail in this report, so that the same methods could easily be reapplied with new specification criteria.

2 Overview of Statistical Specifications

There are three broad components of statistical specifications (Cominsky 1974a, Cominsky 1974b, Weed 1982):

a. Sampling plans.

b. Acceptance plans.

c. Process control plans.

Sampling plans define material properties to be measured, lot size, frequency and size of sampling, sampling procedures, and testing procedures. Acceptance plans define methods for developing acceptance/rejection limits and payment adjustment schemes that reflect product quality. Process control plans define methods for constructing quality control charts and for using their results to decide when action is necessary to adjust product quality.

Sampling Plans

Selection of material characteristics

True performance-related specifications employ relationships between the measured material characteristics and pavement performance to provide the basis for rational acceptance and/or price adjustment decisions (TRB 1996). Consequently, the measured material characteristics must be strongly related to the ultimate performance of the product. To permit effective specification development, the chosen material characteristics must be measurable with low-cost, repeatable test procedures (Weed 1982).

Material characteristics to be used in sampling plans fall into two broad groups (Cominsky 1974b): attributes and variables. For attribute sampling, the acceptability of each sample increment is evaluated by the presence (or absence) of some characteristic or attribute. The acceptability of the work is measured as the proportion of units that do (or do not) possess this characteristic (TRB 1996). An example would be accepting or rejecting a source of

coarse aggregate based on flatness and elongation. The dimensions of each particle would not be measured; each particle would simply pass or fail requirements for both a maximum width/thickness ratio and a maximum length/width ratio. Typically, pavement specifications include requirements for maximum proportions of flat and elongated particles for each sieve size.

In variable acceptance plans, the measured material characteristics are treated as continuous variables. The values of measurements are retained and used, rather than converting them to discrete pass/fail classifications. The acceptability of a lot of material or construction is evaluated using sample statistics, such as the average and standard deviation (TRB 1996). An example would be flexural strength of concrete. The strength values for tested concrete beams are retained for calculating statistics. Specification requirements would address the fact that the variability of strength along a pavement is just as important as the average strength. Most statistical specifications contain elements of both attributes and variable acceptance plans (Weed 1982).

Obtaining samples

Statistical concepts for quality assurance of highway construction are based on the laws of probability. In order for these laws to function properly, the data must be selected by random sampling. A true random sample is one in which all parts of the whole have an equal chance of being chosen for the sample. A table of random numbers is the best device for achieving a strictly random sample. Sampling should not be biased by a set selection pattern or by an inspector seeking either good, bad, or representative parts (McMahon and Halstead 1969, Weed 1982).

A common procedure in acceptance sampling is to consider each submitted lot of product separately and to base the decision of acceptance or rejection of the lot on the evidence of one or more samples chosen at random from the lot. A lot can be defined as a uniquely identified, homogeneous portion of material or construction about which a decision is to be made (McMahon and Halstead 1969). A lot can be defined in terms of a finite number of production items, or in terms of the amount of production completed in a finite time. Examples of lots include 1000 metric tons of surface course asphalt concrete or a day's production. The size of the lot may vary depending on the economics of rejection and on the costs of sampling and testing. The lot size should not be so large that the contractor encounters severe hardship if it is rejected. However, small lots require more sampling and testing, which increases project cost. Lot size must be a compromise (McMahon and Halstead 1969).

Pure random sampling within each lot has been tried and often judged inappropriate for pavement projects because, on occasion, all the samples were clustered together. Stratified sampling, which involves dividing lots into several equal-size sublots, was found to be more appropriate (Weed 1982). Sampling within sublots is still performed randomly, but stratification ensures that the sample increments are spread throughout the lot (Waller 1966).

Stratified sampling conforms to the requirements of random sampling as long as three rules are obeyed (Weed 1982): (1) the number of sublots equals the number of samples to be taken, (2) sublots are of equal size, and (3) samples are selected randomly from within sublots.

As an example of sublots, assume that asphalt concrete is to be sampled from a conveyor at a production facility. If sampling is organized by time, each day's production could be considered a lot. If the sampling plan requires five samples per lot and the plant is in continuous operation, each nine-hour production day could be divided into 5 sublots of 108 minutes each. The time of sampling within each sublot could then be determined by multiplying a random number between 0 and 1 by 108 minutes (Cominsky 1974b).

Sampling plans can also be designed for in-place material. For pavements, use can be made of plan view dimensions. Assume that a project is 2,000 m in length and 4 m in width (single lane). If lot sizes are limited to lane lengths of 500 m, the project could be divided into 4 lots. If each lot is to be represented by 5 samples, each lot could be divided into 5 sublots and then a single sample could be obtained randomly from each sublot. Each sublot would be 100 m in length (=500/5). In order to determine sampling locations, both its longitudinal and transverse coordinates must be randomized. Random numbers are selected for both directions within each sublot. All transverse distances can be measured from either the left or right edge of the pavement, as long as all transverse distances have an equal opportunity for getting selected.

Acceptance Plans

Statistical acceptance plans are formal procedures (quantitative tools) used to decide whether work should be accepted, rejected, or accepted at reduced payment. These decisions are based on probabilities (Weed 1982). An acceptance plan includes a data evaluation scheme and payment adjustment schedule. An acceptance plan must be accompanied by a sampling plan, as described in the previous section.

In the usual buyer-seller relationship, the buyer establishes an acceptance plan that is independent of seller's process control program. In some cases, however, the buyer may elect to use the seller's test results (McMahon and Halstead 1969).

Risks for contractual parties

Whenever samples are used to make statistical inferences about a "lot" of material, the inferences are accompanied by decision risks: the buyer's risk of accepting material of poor-quality and the seller's risk of having adequate-quality material rejected. During the development of an acceptance plan, these risks must be balanced. For a given sample size, reducing the likelihood of accepting poor material usually means increasing the likelihood of rejecting

good materials, and vice versa. To simultaneously reduce both the likelihood of accepting poor materials and the likelihood of rejecting good materials, the sampling plan must be made more discriminating. This usually requires larger sample sizes, which increases the cost of inspection and/or testing (Baecher 1987).

The selection of appropriate probabilities for risks, including both the rejection of good material and the acceptance of poor material, is unavoidably a matter of judgment. However, these probabilities should be related to the criticality of the material characteristic in question, as well as economic considerations. If a material characteristic's failure could result in complete uselessness for the product in which it is contained, then it is a critical characteristic. In such cases, the probability of accepting poor material should be set as close to zero as economically possible. If the product is not critical, the probability of accepting poor material can be higher. For pavement construction, the probabilities associated with rejecting good material and accepting poor material are commonly set at 0.05 and 0.10, respectively (Cominsky 1974b).

Operating characteristic curves

An operating characteristic (OC) curve is a graphical representation of an acceptance plan, which shows the relationship between the quality of a lot and the probability of its acceptance. Operating characteristic curves, which can be produced for either attribute or variable acceptance plans, indicate how well a given sampling plan discriminates between acceptable and non-acceptable lots (Cominsky 1974b). Ideally, an OC curve distinguishes all the acceptable material from all the unacceptable material. An ideal OC curve would resemble Figure 1 if all material that is less than 4 percent defective should be accepted and all material that exceeds 4 percent defective should be rejected. The probability of accepting a high-quality product is 1.0 and the probability of accepting a low-quality product is 0.0 (Mitra 1993). Unfortunately, without flawless inspections on 100 percent of the material, this OC curve is not realistic.

When judgments for acceptance/rejection are based on random samples of data, there must be some finite probability that a low-quality lot will be accepted (β) and that a high-quality lot will be rejected (α). An example of a realistic OC curve is shown in Figure 2. The probability that a product of acceptable quality level (AQL) will be rejected is often referred to as the seller's risk and is often designated by α. The probability that a product of unacceptable quality level (UQL) will be accepted is often referred to as the buyer's risk and is often designated by β. The buyer's risk and the seller's risk can be read directly from an OC curve, as shown in Figure 2.

The shape of an OC curve serves as a qualitative measure for the effectiveness of an acceptance plan (Cominsky 1974b, Mitra 1993). Generally, the slope of the OC curve will increase as the sample size increases, corresponding to improved protection for both the producer and the consumer (Baecher 1987, Grant and Leavenworth 1988).

Pay adjustment schedules

The Transportation Research Board (TRB 1996) defines "pay adjustment schedule" as a pre-established table or equation, used for assigning pay factors associated with estimated quality levels of a given quality characteristic. The pay factors are usually expressed as percentages, which can be applied to the original contract bid price. Pay adjustments can include pay reductions and/or pay increases. The concept of pay reductions recognizes that there is an intermediate zone between exceptional quality and unacceptable quality, permitting specifications to separate rejection and acceptance at full payment (Weed 1982). The region between these extremes is handled as acceptance at reduced pay. Increases in pay serve as incentives for exceptional quality. A popular trend in specification development is to switch from stepped to continuous pay adjustment schedules (Weed 1982).

This concept is not new to the highway construction industry. However, it has been difficult to enforce in the past when specifications have not been based on statistics. Previously, the percentage of the material not complying with specifications could not be properly defined. Also, the effectiveness of the reduced payment clauses has been lost when additional samples are permitted. The additional samples provide for increased chances of finding acceptable measurements for product quality (Nicotera 1974).

Pay adjustments are particularly useful in pavement construction. The designation of acceptable and unacceptable material or construction is not simple. There is usually a "gray area" in which the out-of-limit material or construction may be usable, and removal and replacement operations are not warranted because of delays or other hindrances to traffic. The presence of pay adjustments in a specification provides a method for handling these situations. When pay adjustments are not included in the contract, payment to the contractor must often be arbitrated in after-the-fact negotiations (McMahon and Halstead 1969).

Pay adjustments are ideally developed by relating measures of quality to performance. Otherwise, pay adjustments can be somewhat arbitrary. When relating quality to performance, concepts of engineering economics and liquidated damages come into play (Afferton, Freidenrich, and Weed 1992, Weed 1982). Ordinarily, a pavement is designed to sustain a specified number of load applications before major repair is required. If, due to construction deficiencies, the pavement is not capable of withstanding the design loading, it will fail prematurely. The necessity of repairing this pavement at an earlier date results in an additional expense for the transportation agency. The purpose of pay reductions is to withhold sufficient payment at the time of construction to cover the extra cost anticipated in the future as the result of deficient quality work (Weed 1982b). Conversely, the purpose of pay increases is to share cost savings with the contractor. Cost savings occur in the form of reduced pavement life-cycle costs, which can be achieved by exceptional construction quality.

Improved mix evaluation methods can lead directly to pay factors if noncompliance in a mix exists. Using advanced evaluation methods, the pay

factors will ideally reflect how a mix will perform in the field. For example, Moore et al. (1981), have evaluated mixtures for their performance with respect to fatigue and permanent deformation using a diametral test. The compaction of mixtures to 92 percent density resulted in fatigue lives 45 to 64 percent shorter than mixtures compacted to 96 percent relative density. Deacon, Monismith, and Harvey (1997) have also developed a method for relating changes in asphalt concrete properties to costs for a transportation agency. Their method considers the frequency distributions for air void content, asphalt cement content, and surface course thickness. The affect of these combined factors on the fatigue life of a pavement surface layer is then quantified by Monte Carlo simulation and laboratory fatigue beam data.

In an economical approach to developing pay adjustments, the amount of money withheld must be invested at compound interest at the time of construction to pay for the future cost of restoring the pavement so that it can serve its intended (design) life. However, the following factors, which are typically not included in economic analyses, also deserve consideration (Weed 1978).

a. There will be administrative costs involved in preparing for the premature repair of poor-quality pavements.

b. There will be a cost to the motoring public for earlier and more frequent disruption of traffic to make the necessary repairs.

c. A section of poor-quality pavement will almost certainly make it necessary to overlay a larger section of pavement. For example, if one lane fails, adjacent lanes will often receive an overlay. Similarly, practical considerations will often make it necessary to overlay an entire length of pavement even though only a portion of it has failed.

d. Premature failures, which necessitate additional unanticipated rehabilitation work, could severely restrict the priority-setting capabilities of a transportation agency.

Weed (1978) has proposed that the reduced pay factor for UQL (truly inferior) construction should be set low enough to ensure that the buyer (i.e., the taxpayer) gets his/her money's worth and that sufficient incentive is provided for the contractor to produce quality workmanship. Since item c above, by itself, indicates that the estimated costs of future repairs should be multiplied by a factor of 2 or more, it is felt that a multiplication factor of at least 3 should be used to account for all unquantified items (Weed 1978).

Weed (1982) and Aurilio and Raymond (1995) have demonstrated a life-cycle cost approach to calculating appropriate pay factors. This approach takes into account the original cost of hot mix and allows for two resurfacings within the life span of the pavement. The appropriate pay factor is based on the present-worth cost of construction plus the cost of rescheduling the pavement rehabilitation due to loss of service life. The equation was derived from basic engineering economics formulas; it has been shown to produce a reliable pay factor relationship provided the input values are reasonably accurate (Weed

1982). The appropriate pay factor is calculated as (Aurilio and Raymond 1995):

$$PF = \frac{M_c + (R^{DL} - R^{EL}) \times \left(R_1 + \frac{R_2 R^{EO}}{1 - R^{EO}} \right)}{M_c} \tag{1}$$

where

M_c = cost of hot mix ($/ton)

R = (1 + inflation rate)/(1 + interest rate)

DL = design life (years)

EL = expected life considering construction deficiency (years)

EO = expected life of overlays (years)

R_1 = cost of first resurfacing ($/ton)

R_2 = cost of second resurfacing ($/ton)

Process Control Plans

Process control and inspection sampling are typically performed by the contractor to ensure that the work will meet the requirements of the contract. The contractor must have a sampling, testing, and charting program that will permit predictions of compliance for those material characteristics that are included in a quality assurance program. The contractor must also inspect those items that cannot be sampled and tested (e.g. formwork construction and curing procedures for concrete work). The contractor's control program may require more frequent sampling and testing than that required for an acceptance plan (Cominsky 1974a).

The principal purpose of process control, or quality control, is to identify changes in construction materials or procedures before these changes adversely affect the quality of large quantities of construction product. When a change is detected, efforts are made to find assignable causes and to correct them (Baecher 1987). An assignable cause of change is a relatively large source, usually due to either human error or to a deviation in process functions.

Process control charts, or quality control charts, are graphical methods used for detecting when a change in a continuous production process is attributable to an assignable cause. Statistical methods are necessary to identify assignable causes of change because these changes must be differentiated from random variations in the production process. Random variation, or random error, is inherent in any production environment and is the cumulative effect of many minor influences. Random variation can be minimized but not eliminated. A production process is in control when the mean and variability of a series of

tests on the product remain stable, with the variability due only to random error (Baecher 1987, TRB 1996).

A control chart is constructed by plotting values of sample statistics as a function of time or as a function of some other dimension that is used for ordering sample results (e.g. lot number). If the statistic is analyzed over time and its behavior follows a regular pattern, with variations attributable to random error, the construction process is said to be "in control." If the plotted data demonstrates a trend or bias, moving away from its regular pattern, the construction process is said to be "out of control." In this case, some variation would be attributed to assignable causes.

Control charts can be constructed for lot measurements or sublot measurements. Control charts can also be constructed for individual data points or for moving averages. Moving average values are calculated by averaging several successive point values. They are helpful in deciphering general trends from within highly variable data. Each of these types of process control charts include control limits, in addition to plotted data. These control limits are calculated from expected variabilities; they help the user identify when observed variabilities are in excess of that which would be expected from random causes alone.

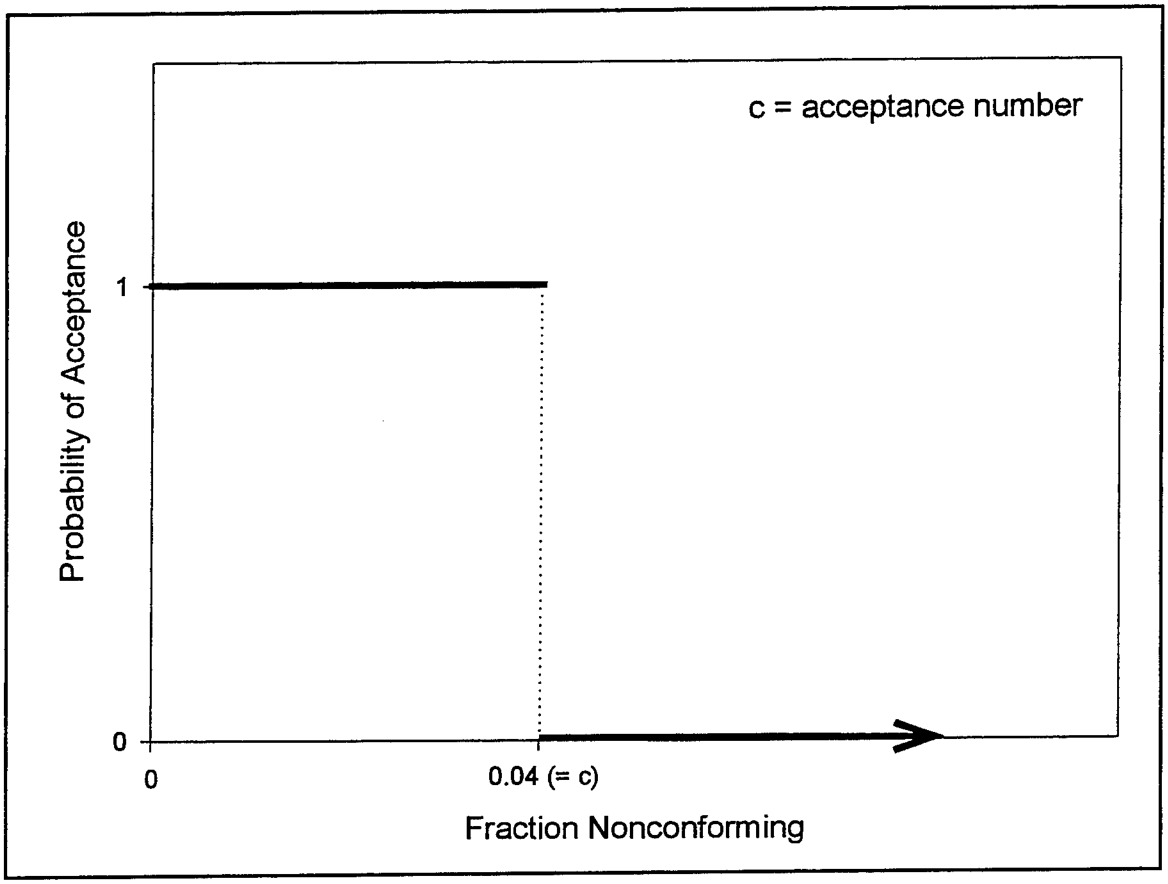

Figure 1. Ideal operating characteristic (OC) curve

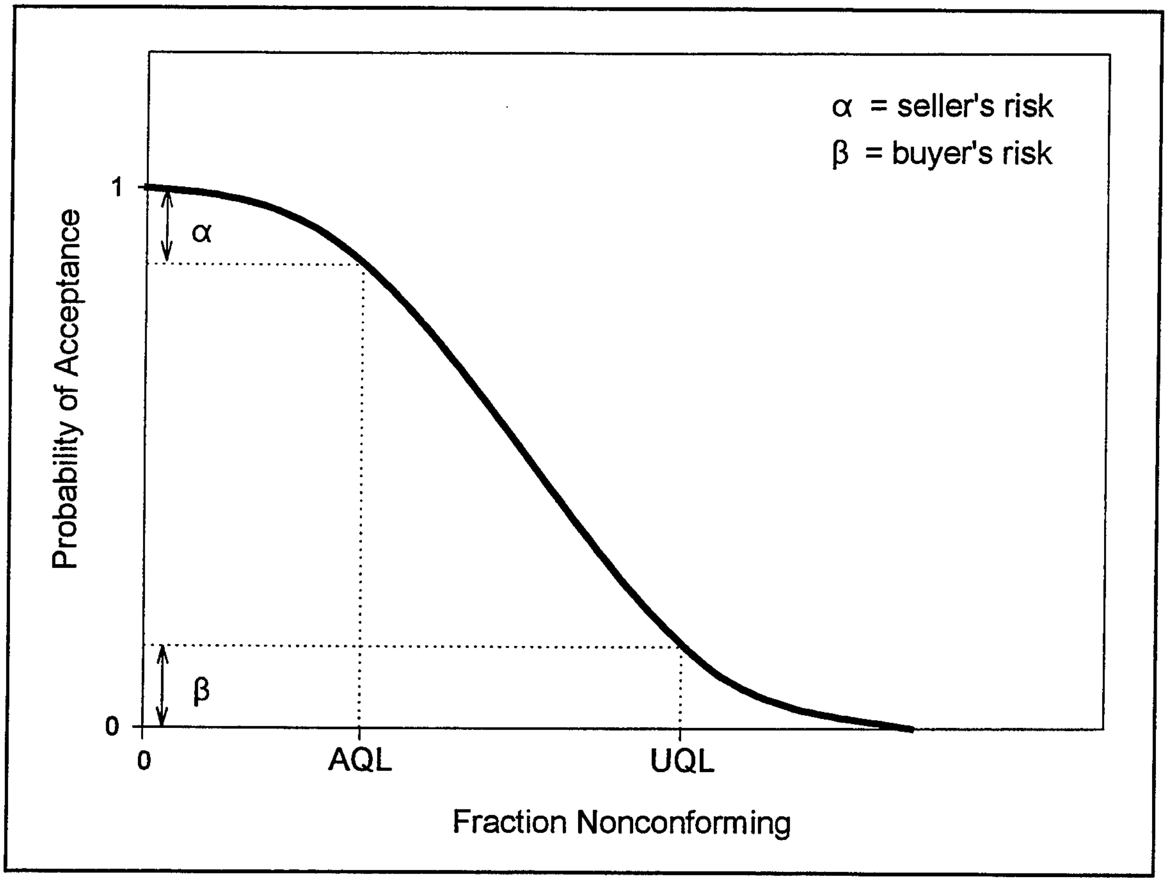

Figure 2. Operating characteristic (OC) curve for a realistic acceptance plan

3 Probability Distributions

This chapter provides brief descriptions of the probability distributions that are essential for understanding process control and acceptance sampling for pavement construction. The hypergeometric distribution and the binomial distribution are necessary for treating material characteristics as attributes. The normal distribution and Student's *t* distribution are necessary for handling material characteristics as variables. The quality index distribution, which is also used for handling material characteristics as variables, will be presented in Chapter 5 after some necessary preliminary discussion of acceptance plans.

Hypergeometric Distribution

The hypergeometric probability distribution is applicable to many engineering problems involving discrete random variables. In this type of problem, *n* items are selected from a finite population containing N items. Within the population, k items are labeled as "successes" and (N-k) items are labeled as "failures." The probability of drawing x successes within the sample size n is generally of interest. The number x is called the hypergeometric random variable and the probability distribution for x is called the hypergeometric distribution. The values for this distribution can be calculated as shown below (Walpole and Meyers 1985).

$$h(x;N,n,k) = \frac{\binom{k}{x}\binom{N-k}{n-x}}{\binom{N}{n}} \quad \textit{where} \quad x=0,1,2,\ldots,n \tag{2}$$

The stacked notation within the equation is described below. The calculation provides the number of combinations found within *N* objects taken *n* at a time.

$$\binom{N}{n} = \frac{N!}{n!(N-n)!} \tag{3}$$

The mean and variance of the hypergeometric distribution are calculated as shown below (Walpole and Myers 1985).

$$\mu = \frac{nk}{N} \tag{4}$$

$$\sigma^2 = \frac{N-n}{N-1} \cdot \frac{nk}{N}\left(1 - \frac{k}{N}\right) \tag{5}$$

Example. Suppose a contractor inspects perforated drainage pipe for integrity and proper hole size as it arrives on site. It arrives in lots of 10 rolls, but he has chosen to inspect only 2 rolls, selected at random. The probability that he would find zero, one, or two defective rolls in a lot that contains three defective rolls can be calculated as follows.

$$P(x=0) = h(0;10,2,3) = \frac{\binom{3}{0}\binom{7}{2}}{\binom{10}{2}} = \frac{7}{15} \tag{6}$$

$$P(x=1) = h(1;10,2,3) = \frac{\binom{3}{1}\binom{7}{1}}{\binom{10}{2}} = \frac{7}{15} \tag{7}$$

$$P(x=2) = h(2;10,2,3) = \frac{\binom{3}{2}\binom{7}{0}}{\binom{10}{2}} = \frac{1}{15} \tag{8}$$

Notice that the probability for x=0, 1, or 2 is equal to unity (7/15+7/15+1/15). These three scenarios account for all possible outcomes when a sample of size two is drawn, so the sum of their probabilities should be unity.

Binomial Distribution

The binomial distribution is also applicable to many engineering problems involving discrete variables. The binomial distribution is similar to the hypergeometric in that each trial has two possible outcomes, typically labeled as "success" and "failure." The difference between binomial and hypergeometric problems is that binomial problems require the probability of success to be the same for each trial. In contrast, the probability of success for the hypergeometric problem changed after each trial because the selected sample units were not returned to the lot. Binomial experiments have the following properties (Walpole and Meyers 1985):

a. The experiment consists of n repeated trials.

b. Each trial results in an outcome that may be classified as a success or a failure.

c. The probability of success, denoted by p, remains constant from trial to trial.

d. The repeated trials are independent.

Even if sample units are not returned to the lot after selection, the binomial distribution is often used as an approximation for the hypergeometric distribution. As long as the lot size is large relative to the sample size ($N/n \geq 10$), permanent removal of sample units from a lot will not significantly affect the probability of success for subsequent sample units (Mitra 1993).

In a binomial problem, the number of x successes in n trials is called the binomial random variable. The probability distribution for this discrete random variable is called the binomial distribution and its value is denoted by b(x; n, p), where p is the probability of success for each trial. Probabilities associated with this distribution can be calculated as shown below (Walpole and Meyers 1985).

$$b(x;n,p) = \binom{n}{x} p^{x}(1-p)^{n-x}, \quad x=0,1,2,\ldots,n \tag{9}$$

The mean and the variance for the binomial random variable, X, can be calculated without constructing the probability distribution, provided that the two distribution parameters *n* and *p* are known.

$$\mu = np \tag{10}$$

$$\sigma^2 = np(1-p) \tag{11}$$

Example. Suppose a contractor is inspecting paving blocks as they are delivered to a job site. Each lot size is 100 blocks and the contractor inspects 3 randomly selected blocks from each lot. Lots are accepted without further inspection if no blocks are found to be chipped or cracked. For the case in which the true proportion defective (p) is 0.1, the probability of finding no damaged blocks in the sample of 3 is shown below.

$$b(0;3,0.1) = \binom{3}{0}(0.1)^0(0.9)^{10} = 0.35 \tag{12}$$

Note that if each block is returned to the lot after inspection and before the selection of the next block, this is a true binomial experiment. Even if the blocks are not returned after inspection, the binomial distribution can serve as a reasonable approximation for the hypergeometric distribution because the sample size is small relative to the lot size.

In specification development, cumulative probabilities are often of interest. For the binomial distribution, one may be interested in the probability that the random variable (x) will be less than or equal to an acceptance number (c). In these cases, x is usually the number of nonconforming items found within the

sample n and the acceptance number is the value that differentiates between acceptance and rejection of a lot. When the probability of obtaining x is represented as P(x), the probability of obtaining x less than or equal to c is represented as $P(x \le c)$ and is calculated as shown below.

$$P(x) = b(x;n,p) = \binom{n}{x} p^{x}(1-p)^{n-x} \tag{13}$$

$$P(x \le c) = \sum_{x=0}^{c} P(x) \tag{14}$$

If n is large, calculating the binomial probabilities and the cumulative binomial probabilities can be cumbersome. Most modern spreadsheet software packages are equipped to handle these calculations. In addition, many textbooks include an appendix with cumulative binomial probabilities tabulated for a range of values for each of x, n, and p.

Normal Distribution

Populations of data

The normal distribution is a continuous distribution that has proved to be useful in many engineering applications. The normal distribution was developed in the eighteenth century when scientists observed regularity in errors of measurement, caused by laws of chance. They called the family of distributions the "normal curve of errors" and fit the following continuous equation, often referred to as the normal probability density function (Johnson 1994).

$$f(y) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-(y-\mu)^2}{2\sigma^2}\right] \tag{15}$$

where

$$-\infty < y < \infty$$

The position and breadth of the resulting normal probability density function is dependent on only two parameters: mean (μ) and standard deviation (σ). The curve is always bell-shaped and symmetric about the mean. The breadth of the curve increases with increasing σ.

$$\mu = \frac{\sum_{i=1}^{N}(y_i)}{N} \tag{16}$$

$$\sigma^2 = \frac{\sum_{i=1}^{N} (y_i - \mu)^2}{N} \tag{17}$$

where

y_i = value for each observation

μ = population mean

N = number of units in the population

The numerator in Equation 17 is often referred to as the "sum of squared deviations" or the "sum of squares." In order to simplify computations, the sum of squares equation can be transformed to a working formula:

$$\sum_{i=1}^{N} (y_i - \mu)^2 = \sum_{i=1}^{N} y_i^2 - \frac{\left(\sum_{i=1}^{N} y_i\right)^2}{N} \tag{18}$$

The calculus required to integrate under normal distribution curves can be quite complex, so probabilities related to areas under these density functions are seldom calculated without the aid of computer software. If software is not convenient for a particular application, tables representing a standard normal distribution are often used to facilitate manual calculations. The standard normal distribution has a mean of zero and a standard deviation of one, resulting in the simplified probability density function shown below.

$$f(y) = \frac{1}{\sqrt{2\pi}} \exp\left[\frac{-y^2}{2}\right] \tag{19}$$

where

$-\infty < y < \infty$

The random variable associated with the standard normal distribution is usually represented by the letter $Z\ [=\{z\}]$. Areas under a normal distribution for any variable $Y\ [=\{y\}]$ can be determined by converting a specific value of y to a value of z using the following equation. The calculated z-value can then be used as input for standard normal distribution tables, such as that shown in Table A1 (Appendix A), to determine the probability of finding measurements less than or greater than y.

$$z = \frac{y - \mu}{\sigma} \tag{20}$$

Example. Assume that a specific mixture of portland cement concrete is required to have a compressive strength greater than or equal to 34 MPa and that the concrete supplier involved has historically reported coefficients of variation for strength in the range of 20 percent. If the average compressive strength for the delivered concrete is 40 MPa, we can use the "Z" tables to calculate the probability that a measured compressive strength will fall below the specified 34 MPA. From the given values for coefficient of variation and mean, the standard deviation of compressive strengths is calculated to be 8 MPA (0.2 × 40 MPa). The z-value that corresponds to a y-value of 34 MPA equals -0.75. Since the standard normal distribution is symmetric, we know that the probability of obtaining a value of z less than -0.75 is equal to the probability of obtaining a value of z greater than +0.75. Therefore, using the standard Z table (Table A1) and interpolation, we can determine that the probability of measuring a compressive strength smaller than the specified 34 MPA equals 0.2266 or 23 percent.

Sample means

The example problems used up to this point have included data sets that were considered to be "populations." A population is a data set representing the entire entity of interest (Freund and Wilson 1993). When dealing with populations, the distribution parameters can be considered to be fixed values. When taking samples from a population, however, the statistics that describe the distribution of sample values cannot be considered to be fixed. Different samples taken from the same population can generate different statistics. A statistic computed from a random sample is therefore a random variable. This inherent variability for sample statistics must be considered whenever small samples are used to make inferences about a population.

All the possible values of a sample statistic can be described by a probability distribution for the statistic, often called a sampling distribution. Characteristics of a sampling distribution can be related to characteristics of the population from which the samples were drawn. Assume samples that include n observations each are drawn from a population, Y [={y}], with mean μ and variance σ^2. As the number of samples drawn approaches infinity, the distribution of sample means, $\bar{y}_i$, will have a mean that approaches μ and a variance that approaches σ^2/n, as shown below.

$$\mu(\bar{y}_i) = \mu \qquad and \tag{21}$$

$$\sigma^2(\bar{y}_i) = \frac{\sigma^2}{n} \tag{22}$$

where

$\mu(\bar{y}_i)$ = mean of sample means

$\sigma^2(\bar{y}_i)$ = variance of sample means

This statement makes intuitive sense as one would expect the sample means to cluster around the population mean and one would expect the variance of sample means to be less than the variance of individual observations. Sample means are referred to as "unbiased" estimates of the population mean.

An additional important characteristic of the distribution of sample means is the "central limit theorem." This theorem states that the distribution of sample means can be closely approximated by the normal distribution, regardless of the population from which the samples are drawn. The size of the samples required to validate this theorem is dependent on the shape of the parent population. If the population resembles normality, sample sizes of 10 or more should be sufficient. Sample sizes of 30 or more should be sufficient for populations of any other shape (Freund and Wilson 1993).

Grant and Leavenworth (1972) stated that even if sample size (n) is small, the distribution of the means of the samples can be very close to normal if the number of samples is sufficiently large. This theory holds true even if the parent population is far from normal. Grant and Leavenworth (1972) reported on a study in which 1,000 samples of size n=4 were taken from two bowls: one containing numbered tags from a rectangular distribution population and one containing numbered tags from a triangular distribution population. Neither of the original populations resembled a normal distribution, however, the distribution of sample means in each case was normal. They reported (Grant and Leavenworth 1972):

"The great practical importance of the normal curve arises even more from its use in sampling theory than from the fact that some observed distributions are described by it well enough for practical purposes. Of great practical significance is the fact that distributions of averages of samples tend to be approximately normal even though the samples are drawn from non-normal populations."

When the distribution of sample means can be assumed to be normal in shape, the standard normal variate Z can be used as a problem-solving tool. Recall the transformation of a random variable from a population to a standard normal variable.

$$z = \frac{y - \mu}{\sigma} \tag{23}$$

Similarly, a sample mean can be transformed from a population to a standard normal variable:

$$z(\overline{y}_i) = \frac{\overline{y}_i - \mu}{\frac{\sigma}{\sqrt{n}}} \tag{24}$$

The denominator in the equation above represents the standard deviation for the distribution of sample means, which can be calculated from the variance of sample means, as shown below. The standard deviation of sample means is often referred to as the "standard error of the mean."

$$\sigma(\overline{y}_i) = \sqrt{\sigma^2(\overline{y}_i)} = \sqrt{\frac{\sigma^2}{n}} = \frac{\sigma}{\sqrt{n}} \tag{25}$$

Example. Suppose that an engineer is planning to construct a parking lot in an area that has a variable water table due to the presence of various types of soil. Suppose also that historical data indicates that the depth to water around the site should follow a near-normal distribution. The mean and standard deviation of the depth to water is 2 m and 0.5 m, respectively. If the engineer is interested in the probability that a sample of 16 measurements will have a mean less than 1.75 m, the Z-table can be used as shown below.

$$z(\overline{y}_i) = \frac{1.75 - 2}{\frac{0.5}{\sqrt{16}}} = -2 \tag{26}$$

From the standard Z table (Table A1), the engineer could see that the probability of getting a z-value less than -2 is approximately 2 percent (0.023). The engineer could then feel confident that the mean of a 16-replicate sample would very rarely be less than 1.75 m.

Sample statistics

The standard normal distribution (Z) is useful when considering "populations" of data for which distribution parameters (mean and standard deviation) can be considered fixed. When using sample data to estimate distribution properties, however, the resulting statistics (mean and standard deviation) cannot be considered fixed. Different samples taken from the same population can generate different statistics. Therefore, when calculating statistics from random samples, the statistics are themselves random variables. All the possible values of a sample statistic can be described by a probability distribution for the statistic, often called a sampling distribution. Characteristics of a sampling distribution can then be related to characteristics of the population from which the samples were drawn.

The calculation of sample variance, s^2, is similar to the calculation of population variance with the exception that the divisor is $(n-1)$, rather than N:

$$s^2 = \frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n-1} \tag{27}$$

where

y_i = value for each observation

$\bar{y}$ = sample mean

n = number of units in the sample

The necessity of using $(n-1)$ as the divisor for the sample variance, rather than n, is a consequence of using a sample statistic, $\bar{y}$, as an estimate of a population parameter, μ, in its calculation. The term $n-1$ in these calculations for sample variance can be referred to as the degrees of freedom for the sample variance statistic. In general, the degrees of freedom for a statistic (ν) is defined as the number of independent observations (n) minus the number of population parameters (m) that must be estimated from sample observations in order to calculate the statistic. In symbols, $\nu = n\text{-}m$ (Spiegel 1990).

As shown previously, the calculation for sample variance requires an estimate for the population mean (μ), which is provided by the sample mean ($\bar{y}$). Therefore, the degrees of freedom for sample variance can be calculated as $\nu = n\text{-}m = n\text{-}1$.

Student's t statistic is calculated in a similar manner as the standard normal, z. The sample statistics s and $\bar{y}$ substitute for σ and μ, respectively. The t distribution is similar to the standard normal distribution in that it is bell-shaped and symmetric about its mean. Relative to normal, however, the t distribution is broader (has fatter tails). This breadth reflects increased dispersion for the variate, which is caused by the uncertainty of using a sample statistic to estimate the population standard deviation. As the sample size increases, confidence in the estimate of the population standard deviation increases, causing the t distribution to become more narrow and to approach normality (Baecher 1987).

$$t = \frac{\bar{y} - \mu}{\frac{s}{\sqrt{n}}} \tag{28}$$

The probability density function that describes the t distribution is tedious to integrate manually, so problems are typically solved with the help of computer software or standard t tables, such as that shown in Table A2 (Appendix A).

Typically, the number 30 is used to differentiate between small samples and large samples. If the sample size is greater than 30, sample variance does not deviate substantially from population variance. Therefore, procedures involving the standard normal (Z) may be applied to these samples. If the sample size is less than 30, sample variance can fluctuate considerably from sample to sample. Therefore, procedures involving Z would not be appropriate; Student's *t* should be used (Walpole and Myers 1985).

Example. Using the water table example shown previously, assume now that the mean of 2 m and the standard deviation of 0.5 m were estimated from the sample of 16 measurements. In this case, the engineer may be interested in the probability that the true mean water table (μ) is less than 1.75 m. This probability can be obtained by calculating the t statistic and comparing its value to Student's standard t probabilities.

$$t = \frac{2 - 1.75}{\dfrac{0.5}{\sqrt{16}}} = 2 \tag{29}$$

This calculation is similar to that for $z(\bar{y}_i)$, but now the calculated statistic is compared to a different distribution. According to Student's *t* distribution, the probability that the true mean is less than 1.75 m is 0.064. This probability is larger than 0.023, which was obtained by the standard normal (Z) distribution. Using sample statistics to estimate population parameters decreased the confidence in the sample results.

4 Acceptance Plans for Attributes

Advantages of acceptance plans for attributes include their simplicity and their ability to combine multiple discrete inspection decisions into a single yes/no decision. For example, an aggregate blend may include five size fractions that need to be tested for flatness and elongation. An acceptance plan for attributes would permit each sieve size to be classified as "within" or "outside of" tolerance limits. Four aggregate samples would provide 20 (=4x5) test results. Judgments concerning the lot of aggregate could then be based on all 20 test results. For example, the lot could be rejected if six or more test results fall outside the limits. This grouping technique simplifies analyses but should only be applied when each test result in the group can be considered of equal importance (Cominsky 1974).

A disadvantage of acceptance plans for attributes is the need for relatively large sample sizes. When handling material characteristics as attributes, rather than as variables, information is lost (i.e., measured values are not retained). Consequently, relative to acceptance plans for variables, those for attributes require larger sample sizes and/or higher frequencies of sampling for the same degree of protection to the contractual parties (Cominsky 1974).

Sampling discrete variables for pavement construction specifications often does not include the replacement of sample items back into lots. Ordinarily, these situations should be represented by a hypergeometric distribution. However, most sample sizes in statistical specifications are small relative to lot sizes, so a binomial approximation for the hypergeometric distribution is common. Binomial approximations will be used for further discussion.

The binomial distribution can be used to calculate probabilities related to quality assurance decisions for attributes, including those needed to construct operating characteristic curves. The operating characteristic curves will clearly show seller risks and buyer risks. An example problem with a single decision criterion (nonconformance value) will demonstrate how to decide whether to accept or reject a lot. An example problem with dual decision criteria (two different nonconformance values) will demonstrate the use of payment adjustments.

When applying attribute acceptance plans, some quality goals must be set for the inspection. The acceptable quality level (AQL) identifies the fraction of

the product that can be defective, without substantially affecting its final quality. Although 100 percent compliance would generally be preferred, such a demand would result in material prices that would be out of proportion with the supposed increase in value of the material. Some small fraction of defective material must be permitted due to the unavoidable variability that accompanies any material or production process (Cominsky 1974). An unacceptable quality level (UQL) is also set to identify the level of quality at which a product is deemed unsatisfactory.

Establishing Limits and Criteria

Single decision criterion

Example. Suppose a buying agency in a pavement contract accepts smoothness based on attribute sampling. A sample of straight-edge measurements are performed and each measurement results in a pass/fail decision. The pass/fail decision is based on a comparison between the maximum allowable deviation between straight-edge and pavement and the actual maximum deviation. Assume the sample size (n) for a lot is 20 and assume that the buying agency had previously set the acceptable quality level (AQL) and the unacceptable quality level (UQL) at fractions defective of 0.10 and 0.30, respectively. The agency had also decided that the pavement would be rejected if 5 or more measurements fail. The highest permissible number of nonconforming measurements, which would be 4 for this example, is often referred to as the acceptance number (designated "c"). This value is the "single decision criterion" referenced by the title of this section.

The seller's risk (often designated α) can be calculated as the probability that 5 or more measurements will fail when the true fraction defective is 0.10. The buyer's risk (often designated β) can be calculated as the probability that 4 or fewer measurements will fail when the true fraction defective is 0.30. Both risks are calculated from cumulative binomial distributions, as shown below. The buyer's risk is calculated first.

$$P[x \leq c \; given \; p=0.3] = P[x \leq 4 \,|\, p=0.3] = \sum_{x=0}^{4} P(x) \tag{30}$$

where

$$P(x) = \binom{20}{x} p^{x}(1-p)^{n-x} = \frac{20!}{x!(20-x)!}(0.3)^{x}(0.7)^{20-x} \tag{31}$$

This cumulative probability can be calculated by hand or by spreadsheet function to be 0.238. While rejecting lots with 5 or more nonconforming smoothness measurements, the buying agency has a risk of approximately 24 percent that the true fraction defective is 0.30 (UQL) or more.

The seller's risk can be stated as the probability that a rejected lot, which would have 5 or more nonconforming measurements, actually had only 0.10 (AQL) fraction defective.

$$P[x > c \text{ given } p{=}0.1] = P[x > 4 \,|\, p{=}0.1] = 1 - \sum_{x=0}^{4} P(x) \tag{32}$$

where

$$P(x) = \binom{20}{x} p^{x}(1-p)^{n-x} = \frac{20!}{x!(20-x)!}(0.1)^{x}(0.9)^{20-x} \tag{33}$$

The cumulative probability term can be calculated by hand or by spreadsheet function to be 0.960. Therefore, the seller's risk is approximately 0.04 (1-0.96).

All this risk information can be displayed in an operating characteristic (OC) curve, as shown in Figure 3. Each point on the curve represents a cumulative binomial distribution calculation with a different value for percent defective, p. The cumulative binomial distribution provides the probability of acceptance. The buyer's risk (β) and the seller's risk (α) can be obtained from the OC curve, given the AQL and the UQL, as shown.

Dual decision criteria

An attribute sampling plan with two decision criteria allows rejection and acceptance at full payment to be based on different fractions of defective material. The separation of rejection and acceptance at full pay provides a region in-between (a gray area) that can be handled uniquely. In some cases, when a lot is found to have a fraction defective in the gray area, specifications permit another sample to be taken to provide a larger base of data for the impending decision. This is often called a double sampling plan. Double sampling plans offer a psychological advantage over single sampling plans in that the seller has a second chance if the first sample is a borderline case (Mitra 1993).

An additional alternative for the gray area is to implement pay adjustments. In this type of acceptance plan, a lot receives full payment if its fraction of defective material is less than or equal to the acceptance limit (c) and it receives no payment if its fraction defective is greater than the rejection limit (r). A lot that has a fraction defective in the gray area receives partial payment. The lot is neither rejected nor payed in full. The bid price for the lot is multiplied by a fraction prior to payment. This type of acceptance plan has a psychological advantage in that decisions related to good and bad products are not abrupt.

Relative to the single criterion plan, the dual criteria plan is slightly more complex. However, as long as the rules are stated clearly in the specification, the dual criteria plan should result in fewer disputes.

Example. Using the example of straight-edge measurements, assume the sample size (n) is still 20 and assume that the AQL and UQL are still 0.10 and 0.30, respectively. Similar to the previous example, a lot will be rejected if 5 or more defective units are found. However, in this second example, a lot will receive 100 percent pay only if the number of defective units is 2 or less. The buyer's risk is therefore calculated as the probability that 2 measurements fail when the true fraction defective is 0.30. The seller's risk is still calculated as the probability that more than 4 measurements will fail when the true fraction defective is 0.10. Both risks are calculated from cumulative binomial distributions, as shown below. The buyer's risk is calculated first.

$$P[x \leq c \text{ given } p=0.3] = P[x \leq 2 \,|\, p=0.3] = \sum_{x=0}^{2} P(x) \tag{34}$$

where

$$P(x) = \binom{20}{x} p^{x}(1-p)^{n-x} = \frac{20!}{x!(20-x)!}(0.3)^{x}(0.7)^{20-x} \tag{35}$$

This cumulative probability can be calculated by hand or by spreadsheet function to be 0.036. While paying full bid price for lots with 2 or less nonconforming smoothness measurements, the buying agency has a risk of approximately 4 percent that the true fraction defective for these lots is 0.30 (UQL).

The seller's risk can be stated as the probability that a rejected lot, which would have more than 4 nonconforming measurements, is actually only 0.10 (AQL) defective. This risk remains the same as the single criterion plan, at approximately 0.04 (1-0.96). The dual plan in this example has permitted the buyer and the seller to share the risk equally.

This risk information can be displayed on two operating characteristic (OC) curves, as shown in Figure 4. One curve was produced with the acceptance number, *c*, and the other curve was produced with the rejection number, *r*. Each point on each curve represents a cumulative binomial distribution calculation with a different value for percent defective, p. The cumulative binomial distribution provides the probability of acceptance. Given the appropriate AQL and UQL, the buyer's risk (β) and the seller's risk (α) can be obtained from the two OC curves, as shown.

Calculating Payment

Payment calculations for the single criterion example are simple. In this example, the sample size (n) was 20 and the acceptance number (c) was 4. If 4 or fewer straight-edge measurements were nonconforming, the seller would receive 100 percent payment. If 5 or more straight-edge measurements were nonconforming, the lot would be rejected and the contractor would receive no payment. If exactly 5 measurements were nonconforming, the potential for ill

feelings between parties is obvious. Some provision for additional sampling would reduce the potential for disputes.

Payment calculations for dual criteria specifications include pay adjustments in the gray area between the acceptance number (c) and the rejection number (r). Payment adjustments for attributes are typically based on discrete, linear scales. The seller receives 100 percent payment if the number of defective units is (c) or less. The seller receives no payment (lot is rejected) if the number of defective units is more than (r). The bottom of the sliding payment scale, which is imposed if precisely r units are defective, is set at a value that reflects the added costs to the buyer. These added costs are caused by the poor quality product. For the previous example, one must decide on the costs to the buyer that result from owning a pavement with a smoothness that is 20 percent ($r = 4/20$) nonconforming. Added costs could include an increased rate of deterioration for a pavement with a rough surface. These estimates of added costs are rarely strict, concise calculations. They often are merely based on reasonable assumptions and logical thought processes.

For the previous example, assume that a pavement smoothness at the rejection limit is estimated as costing the buyer 10 percent of the bid price. This cost is relative to a pavement that receives 100 percent payment, with a smoothness that is only 10 percent ($c = 2/20$) nonconforming. Typically, the payment scale would step linearly through the discrete numbers of nonconforming measurements. If 3 measurements did not conform to specified tolerances, the percent payment would be 95 percent. If 4 measurements did not conform to specified tolerances, the percent payment would be 90 percent.

This problem can be used to emphasize two important aspects of the development of specifications. The first aspect is random sampling. Statistical specifications can only function properly if the QC/QA testing is performed randomly. In the previous problem, decisions concerning acceptance and rejection of a lot could be affected substantially by purposely selecting even a few locations for measuring smoothness, based on the appearance of the road surface. The second aspect is sample size. The previous problem used a relatively small sample size to make costly judgements related to lots of asphalt concrete. If lot size was increased, party risks could be adjusted in smaller increments, permitting improved control. Larger samples would also improve party confidence in the decisions made from sample results.

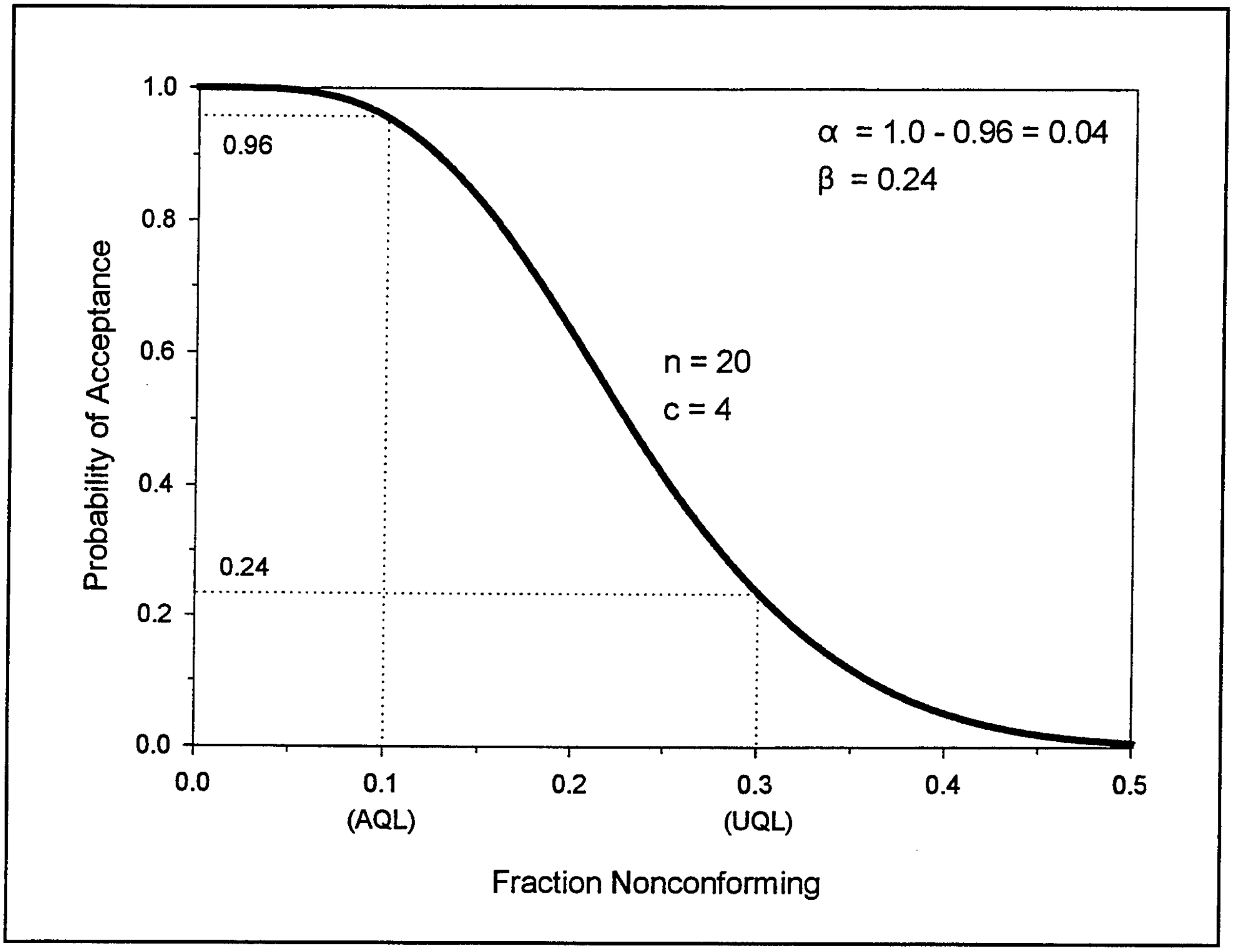

Figure 3. OC curve for attributes with a single decision criterion

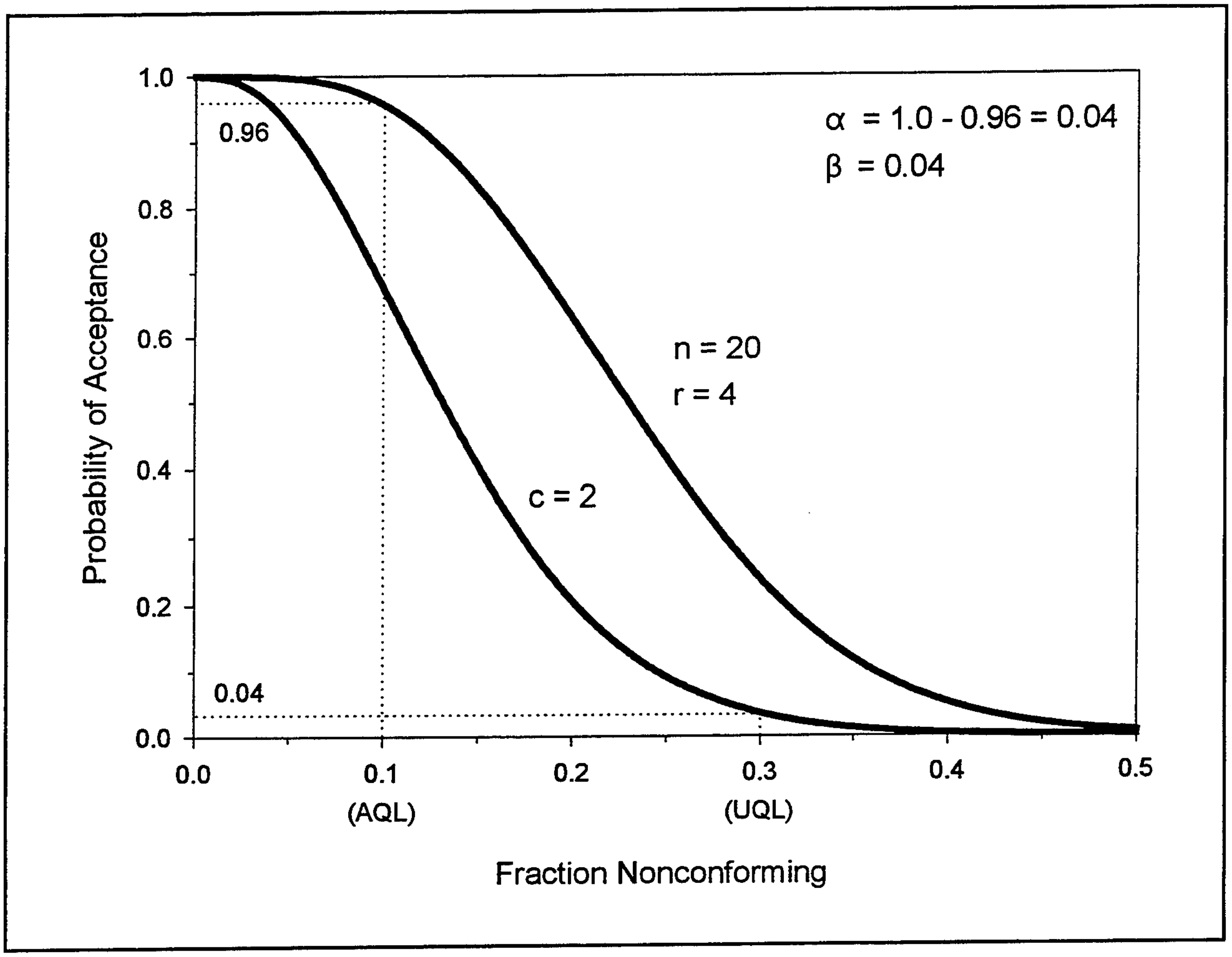

Figure 4. OC curve for attributes with a dual decision criterion

5 Acceptance Plans for Continuous Variables

During tests for conformance in an acceptance plan for variables, measured values are retained rather than converted to simple yes/no decisions, as they were for attribute acceptance plans. One immediate advantage of the acceptance plan for variables is this retention of information, which results in smaller sample size requirements (Cominsky 1974). An additional advantage of acceptance plans for variables is that they produce continuous results, rather than discrete results. Continuous results are more suitable for developing adjusted pay schedules (Weed 1982).

A comparison between attribute sampling plans and continuous variable sampling plans reveals the following (Grant and Leavenworth 1988, Mitra 1993).

a. For comparable α, β, AQL, and UQL, continuous variable plans have smaller sample sizes than attribute plans.

b. Continuous variable sampling plans provide more information, which may provide insight into areas that deserve attention for quality improvement.

c. Errors of measurement are more likely to be disclosed with continuous variable information.

d. Unit inspection costs are usually higher for continuous variable sampling plans (administration costs and test devices).

e. In order to make inferences for the continuous variable plans, the distribution for the quality characteristic must be known or estimated.

f. Multiple quality characteristics are difficult to combine for a single acceptance decision in continuous variable plans. In contrast, multiple quality characteristics can be combined readily in attribute plans.

Acceptance plans for continuous variables may take one of two forms (Cominsky 1974): (1) those that control the average and standard deviation directly and (2) those that control the fraction of nonconforming material. The term "nonconforming" applies to the fraction of material that falls outside of

predefined specification limits. These two types of continuous variable acceptance plans are applicable to different situations. For example, the ability for a soil slope to resist large slope instabilities more often depends on average soil characteristics, so plan type (1) would be applicable. Conversely, the potential for internal erosion of soil fill is a function of the least compacted areas, so plan type (2) would be applicable (Baecher 1987).

This chapter will address specifications that control the fraction nonconforming because they are most suitable for pavement construction. The premature functional failure of a pavement is typically instigated by local areas of nonconforming material, rather than overall average properties. In the discussions that follow, the distributions of material characteristics are assumed to be normal in shape. For most cases concerning pavement material characteristics, normality is a valid assumption (Freeman and Grogan 1997). The assumption of normality permits the use of standard statistics tables, which facilitates calculations. The ideas presented below can be adopted to other distribution shapes, but these cases will not be addressed in this report.

Acceptance plans for variables can involve single (one-sided) or dual (two-sided) specification limits. A single specification limit includes either a lower limit (LL) or an upper limit (UL) requirement. A dual specification limit includes both a LL and an UL. Acceptance plans for variables can base acceptance/rejection decisions on either a single criterion or dual criteria. A single criterion is used when a simple pass/fail decision is appropriate. Dual decision criteria are appropriate when passing and failing should be separated by an intermediate zone where conformance decisions require special handling (e.g., pay adjustments).

Acceptance plans are introduced in this chapter in two stages. First, the limits and criteria are developed for each plan in a manner that maintains predefined risks for the contractual parties. Secondly, example data are used to calculate fractions of nonconforming material for selected plans. The acceptance plans are presented in these two stages because each stage requires slightly different assumptions. While developing limits and criteria, the variability of the material characteristic in question is assumed to be known. Although a value does not actually have to be assigned to calculate risks, representative values should be entered to ensure that the limits are realistic. While calculating fractions of nonconforming material, the variability of material characteristics are estimated from samples of data.

Reference Distributions

Available literature includes many methods for calculating party risks and fractions of nonconforming material. These various methods use one or more of several frequency distributions, including the standard normal distribution, Student's t distribution, and the quality index (Q) function. The Q function was developed specifically for inspection plans on continuous variables for the purpose of using sample data to estimate the fraction of a normal population

that lies outside of a given interval (Lieberman and Resnikoff 1955). The decision of which distribution to use depends on several factors, including the extent of knowledge concerning material variability, the anticipated number of replicates per sample, and the anticipated fraction defective. The differences between these distributions decrease as both the number of replicates and fraction nonconforming increase.

In this report, calculations associated with specification development are based on the assumption that material variability is known (or at least can be estimated with reasonable accuracy). Therefore, these calculations use the standard normal (Z) distribution as a reference. Advantages of using the Z-distribution include its simplicity, its familiarity to most engineers, and its availability in most spreadsheet software as a built-in function. Calculations associated with estimating fraction nonconformance for lots of material are based on the assumption that variability will be estimated from the sample data (i.e., sample standard deviation). These calculations require the use of the quality index (Q).

The calculation of Z, *t*, and Q are shown below. Both Z and Q are used in this chapter. Student's *t* is included due to its familiarity to most engineers. The equations change slightly depending on whether the limit in question is below the mean (LL) or above the mean (UL). The changes are intended only to keep the calculated statistics positive. The similarities in the equations shown are evident, with exception for the fact that Z uses population parameters, while *t* and Q use sample statistics.

$$z(lower) = \frac{mean - lower\,limit}{standard\ deviation} = \frac{\mu - LL}{\sigma} \qquad (36)$$

or

$$z(upper) = \frac{upper\ limit - mean}{standard\ deviation} = \frac{UL - \mu}{\sigma} \qquad (37)$$

$$t(lower) = Q(lower) = \frac{mean - lower\ limit}{standard\ deviation} = \frac{\bar{y} - LL}{s} \qquad (38)$$

or

$$t(upper) = Q(upper) = \frac{upper\ limit - mean}{standard\ deviation} = \frac{UL - \bar{y}}{s} \qquad (39)$$

The use of z values implies that results will be compared to the standard normal distribution. The use of Q values implies that results will be compared to the standard quality index distribution. The use of *t* values implies that results will be compared to Student's *t* distribution. The standard normal distribution is independent of sample size, but the standard Q and Student's *t* both change shape with changes in sample size (Mitra 1993). Most modern

spreadsheet software packages include both the standard normal distribution and Student's t as built-in functions. Standard quality index values are usually obtained by accessing tables in either the U.S. Military Standard 414 (USDOD 1957), the American Society of Quality Control standard ANSI/ASQC Z1.9 (ASQC 1980), or any other document that has reproduced these tables. For reference purposes, this report includes standard normal, Student t, and quality index values in Appendix A. In addition, Appendix B demonstrates a method for obtaining quality index values using the beta distribution. This should facilitate spreadsheet calculations for the quality index because most modern spreadsheet software packages have built-in functions for the beta distribution.

In order to clarify differences between Q and t, their respective estimates for fraction nonconforming are compared in the following text under various situations. This comparison is important because Q and t serve different purposes in statistical theory. Fraction nonconforming, as determined by both Q and Student's t, are shown for various sample sizes in Figures 5 through 7. Estimates for fraction nonconforming, based on the standard normal distribution, are included in the figures for reference. It is apparent that the differences in the calculations are highest when fraction nonconforming is small and when sample size is small. For similar calculated deviations from mean values, Student's t predicts a higher fraction nonconforming than Z. For similar calculated deviations from mean values, Q predicts a lower fraction nonconforming than Z. Student's t and Q are both different from Z due to the uncertainty associated with estimating standard deviation from a sample. These differences are largest for small sample sizes because confidence in standard deviation estimates decreases as sample size decreases.

Student's t and Q divert from Z in opposite directions because they were developed for different purposes. Student's t was developed for determining whether or not sample means can be assumed to originate from the same population. The use of Student's t essentially causes the sample probability distributions to be more broad. Increased broadness makes the detection of significant differences between sample means more difficult. This is the penalty for using sample statistics, rather than population parameters. The Q was developed for estimating the probability of finding observations outside designated deviations from a mean (i.e., estimating the area within the "tails" of a distribution). The use of Q essentially causes the probability distributions to be more narrow. Decreased broadness makes the detection of nonconforming material (i.e., large deviations from mean) more difficult. This is the penalty for using sample statistics, rather than population parameters. While Student's t is appropriate for use in specifications governing mean values, Q is appropriate for use in specifications governing fractions of nonconforming material (Duncan 1959).

Establishing Limits and Criteria

The standard deviation of the appropriate material characteristic is assumed to be known for this portion of specification development (calculated as σ). The use of σ for calculations needed to ensure that specification limits and

criteria are realistic is justified because there exist plenty of publications that document variabilities associated with pavement construction (e.g., Freeman and Grogan 1997, Harr 1987, and Yoder and Witczak 1975). These published variabilities can be used to check the reasonableness of specification criteria. The calculation of party risks is also covered in this section of text; risk calculations are independent of material variability.

Single specification limit, single decision criterion

The first type of specification to be addressed involves a single specification limit, such as that used for the compaction of soils. Typically, soil has a requirement for a minimum dry density without any maximum dry density requirement. The specification should be written to control the fraction of soil density that falls below the predefined lower limit (LL). However, this type of specification can use a single upper specification limit (UL) just as easily. The relationships between the LL and both the acceptable quality limit (AQL) and the unacceptable quality limit (UQL) are shown in Figure 8. Each of the distributions shown represents a single population of material characteristics.

Example. Suppose four density tests are to be performed for a lot of compacted subgrade material (n=4). The lower limit (LL) of acceptability for dry density is specified to be 90 percent of maximum, as determined by modified Proctor procedures. The acceptability criterion (c), the AQL, and the UQL would all be based on fractions of defective material. This example does not include a rejection limit (r) because the specification is to be designed with a single decision criterion. Assume for this example that AQL=0.05, UQL= 0.20, and c=0.10. Also assume that 4 percent has been determined to be a reasonable standard deviation, based on historical records.

The seller's risk is the probability that the calculated fraction defective will exceed 0.10 (c) if the true (mean) fraction defective is 0.05 (AQL). The buyer's risk is calculated as the probability that the calculated fraction defective will be less than 0.10 (c) if the true (mean) fraction defective is 0.20 (UQL). The first step in calculating these probabilities is determining the means that correspond to fractions defective of AQL, c, and UQL.

For μ_{AQL}:

$$z_{AQL} = z_{0.05}(one\text{-}tail) = 1.645 \tag{40}$$

$$1.645 = \frac{\mu_{AQL} - LL}{\sigma} = \frac{\mu_{AQL} - 90}{4} \tag{41}$$

$$\mu_{AQL} = 96.58 \ percent \tag{42}$$

For μ_C:

$$z_c = z_{0.10}(one\text{-}tail) = 1.282 \tag{43}$$

$$1.282 = \frac{\mu_c - LL}{\sigma} = \frac{\mu_c - 90}{4} \tag{44}$$

$$\mu_c = 95.13 \; percent \tag{45}$$

For μ_{UQL}:

$$z_{UQL} = z_{0.20}(one\text{-}tail) = 0.842 \tag{46}$$

$$0.842 = \frac{\mu_{UQL} - LL}{\sigma} = \frac{\mu_{UQL} - 90}{4} \tag{47}$$

$$\mu_{UQL} = 93.37 \; percent \tag{48}$$

The seller's risk and the buyer's risk can now be calculated using the distribution of means, rather than the distribution of values within a single population. The distribution of means are more narrow, as shown in Figure 9. The seller's risk (α) is calculated as the probability of finding a mean below c when the true mean is at μ_{AQL}.

$$z_\alpha = \frac{\mu_{AQL} - \mu_c}{\frac{\sigma}{\sqrt{n}}} = \frac{96.58 - 95.13}{\frac{4}{\sqrt{4}}} = 0.725 \tag{49}$$

From the standard z tables, the seller's risk (α) is found to be 0.234 (or 23.4 percent).

The buyer's risk (β) is calculated as the probability of finding a mean above c when the true mean is at μ_{UQL}.

$$z_\beta = \frac{\mu_c - \mu_{UQL}}{\frac{\sigma}{\sqrt{n}}} = \frac{95.13 - 93.37}{\frac{4}{\sqrt{4}}} = 0.880 \tag{50}$$

From the standard z tables, the buyer's risk (β) is found to be 0.189 (or 18.9 percent).

The seller's risk and the buyer's risk can also be calculated using the distribution of calculated z values. Recall that z_{AQL}, z_c, and z_{UQL} were calculated using the distribution of material characteristics from a single population. These z values are themselves members of distributions of means where the standard deviation is calculated below, recognizing that the standard deviation of the standard normal (Z) distribution is unity.

$$\sigma_{\bar{z}} = \frac{\sigma_z}{\sqrt{n}} = \frac{1}{\sqrt{n}} \tag{51}$$

The seller's risk and the buyer's risk can be recalculated using the distributions of mean standard normal values. The corresponding distributions are shown schematically in Figure 10.

$$z_\alpha = \frac{z_{AQL} - z_c}{\frac{1}{\sqrt{4}}} = \frac{1.645 - 1.282}{\frac{1}{\sqrt{4}}} = 0.726 \tag{52}$$

$$z_\beta = \frac{z_c - z_{UQL}}{\frac{1}{\sqrt{4}}} = \frac{1.282 - 0.842}{\frac{1}{\sqrt{4}}} = 0.880 \tag{53}$$

The calculated α and β are the same as those shown previously: 0.234 and 0.189, respectively.

Continuing with the concept that any observed fraction nonconforming is actually an observation within a distribution, specifications such as this example can be represented by an operating characteristic (OC) curve. The probability of accepting the lot is calculated for several reasonable values of fraction nonconforming, in addition to those needed to calculate α and β. The OC curve for the example just presented is shown in Figure 11.

The reasonableness of assigned limits and the resulting risks can now be examined from the information gathered. The risks appear to be relatively high. Risks for pavement construction are typically on the order of 15 percent or less. The relative densities required to attain a fraction defective equal to c, or even AQL, appear to be reasonable. To achieve c or AQL, the mean relative density of soil would need to be 95.1 percent or 96.6 percent, respectively. Therefore, the lower limit of 90 percent for soil density appears to be reasonable. In order to reduce party risks, a second attempt at developing the specification could include a larger sample size, a change in the acceptance limit, c, or the implementation of dual decision criteria, as described in the next section.

Single specification limit, dual decision criteria

Similar to the use of dual criteria for attribute acceptance plans, the use of dual criteria for continuous variable plans permits the incorporation of pay adjustments to handle borderline cases. A compaction problem similar to that shown previously will be used for demonstration purposes. The primary difference between the problems will be the method of designating acceptable fractions of defective material.

Example. Assume the compaction specification for this example requires four density tests for each lot (n=4), similar to the previous example. The lower limit of acceptability for relative dry density is still 90 percent of maximum, as determined by modified Proctor procedures. The AQL, c, and UQL, in terms of fraction defective, are still 0.05, 0.10, and 0.20, respectively.

Contrary to the specification in the previous problem, this specification includes a rejection criterion (r) for fraction nonconforming of 0.15.

This type of problem must be characterized by two OC curves: one for the acceptance criterion (c) and one for the rejection criterion (r). The seller's risk is estimated as the probability that the calculated fraction nonconforming will exceed 0.15 (r) if the true (mean) fraction defective is 0.05 (AQL). The buyer's risk is estimated as the probability that the calculated fraction nonconforming will be less than 0.10 (c) if the true (mean) fraction nonconforming is 0.20 (UQL). These probabilities can be calculated by comparing their corresponding standard normal variates, z. The values $z_{0.05}$, $z_{0.10}$, and $z_{0.20}$ were calculated in the previous problem to be 1.645, 1.282, and 0.842, respectively. The value for $z_{0.15}$ is calculated below.

$$z_r = z_{0.15}(\mathit{one\text{-}tail}) = 1.036 \tag{54}$$

The seller's risk (α) can be calculated using the distribution of z means as follows.

$$z_\alpha = \frac{z_{AQL} - z_r}{\frac{1}{\sqrt{n}}} = \frac{z_{0.05} - z_{0.15}}{\frac{1}{\sqrt{4}}} = \frac{1.645 - 1.036}{\frac{1}{\sqrt{4}}} = 1.218 \tag{55}$$

The probability that z will exceed 1.218 is 0.112 (11.2 percent). This is the seller's risk (α). The buyer's risk (β) would remain unchanged from the previous example, at 0.189 (18.9 percent). This set of risks is more appropriate than those in the previous section: the seller's risk is commonly expected to be smaller than the buyer's risk.

Again, the operating characteristic (OC) curve is constructed by calculating the probability of accepting the lot for several reasonable values of fraction defective, in addition to those used to calculate α and β. Two OC curves are needed to represent this problem, similar to the two OC curves needed for attribute variables with dual criteria. The OC curves for the example just presented are shown in Figure 12. Note that the region between the curves is addressed by pay adjustment factors, which will be discussed in a later section.

Double specification limits, single decision criterion

Double specification limits are required when a material property must be controlled within a range of values. The following example demonstrates the use of double specification limits for quality assurance of binder content for asphalt concrete.

Example. Suppose six extraction tests are performed for each lot of asphalt concrete mixture (n=6). The lower limit (LL) of acceptability for binder content is specified to be 5.0 percent, while the upper limit (UL) of acceptability is specified to be 7.0 percent. Assume for this example that AQL=0.05,

UQL=0.15, and c=0.075. Also assume that historical records reveal that a common standard deviation is 0.4 percent.

Before proceeding with buyer and seller risk calculations, the case of dual criteria requires some checks. First of all, one must check that these fractions of nonconforming material can be achieved. The smallest fraction nonconforming occurs when the calculated mean splits the lower limit (LL) and the upper limit (UL). Using the assumed standard deviation, this calculation proceeds as follows.

$$z_{(two-tail)} = \frac{\mu - LL}{\sigma} = \frac{6-5}{0.4} = 2.5 \tag{56}$$

$$P(z > |2.5|) = 0.0124 \tag{57}$$

If the mean of a lot splits LL and UL and if the assumed standard deviation is achieved, then the estimated fraction defective would only be 0.0124. Since this value is less than AQL (0.05), the specification appears to be realistic.

The second check is to determine whether the calculated z values can be treated as one-tail tests when calculating fractions of defective material. This decision requires the calculation of the process mean that corresponds to the smallest specified fraction defective (AQL). Treating this calculation initially as a one-tail test, the appropriate z statistic is shown below. This z_{AQL} can then be used to calculate the corresponding mean asphalt cement content.

$$z_{AQL} = z_{0.05}(one\text{-}tail) = 1.645 \tag{58}$$

$$1.645 = \frac{\mu_{AQL} - LL}{\sigma} = \frac{\mu_{AQL} - 5.0}{0.4} \tag{59}$$

$$\mu_{AQL} = 5.66 \ percent \tag{60}$$

In addition to the fraction defective below LL, there is potential for fraction defective above UL. Since μ_{AQL} is closer to LL the fraction defective below LL is primary (larger) and the fraction defective above UL is secondary (smaller). The secondary fraction defective is calculated as follows.

$$z_{AQL}(secondary) = \frac{UL - \mu_{AQL}}{\sigma} = \frac{7-5.66}{0.4} = 3.35 \tag{61}$$

$$P(z > 3.35) = 0.0004 \tag{62}$$

The secondary component of fraction defective for AQL accounts for less than 1 percent of the total, so it can be neglected. The secondary components of fraction defective for c and UQL would be even smaller. These findings support the previous statement that the specification is reasonable. We are now ready to proceed with risk calculations, treating them as one-tail problems.

Similar to the example that involved a single specification limit, the seller's risk is calculated as the probability that the fraction defective will exceed 0.075 (c) if the true (mean) fraction defective is 0.05 (AQL). The buyer's risk is calculated as the probability that the calculated fraction defective will be less than 0.075 (c) if the true (mean) fraction defective is 0.15 (UQL). These probabilities are calculated by comparing their corresponding standard normal values.

$$z_{AQL} = z_{0.05}(one\text{-}tail) = 1.645 \tag{63}$$

$$z_c = z_{0.075}(one\text{-}tail) = 1.440 \tag{64}$$

$$z_{UQL} = z_{015}(one\text{-}tail) = 1.036 \tag{65}$$

The seller's risk (α) can be calculated using the distribution of z means as follows.

$$z_\alpha = \frac{z_{AQL} - z_c}{\frac{1}{\sqrt{6}}} = \frac{1.645 - 1.440}{\frac{1}{\sqrt{6}}} = 0.502 \tag{66}$$

The probability that z will exceed 0.502 is 0.308 (30.8 percent). This is the seller's risk. The buyer's risk (β) can also be calculated using the distribution of z means as follows.

$$z_\beta = \frac{z_c - z_{UQL}}{\frac{1}{\sqrt{6}}} = \frac{1.440 - 1.036}{\frac{1}{\sqrt{6}}} = 0.990 \tag{67}$$

The probability that z will exceed 0.990 is 0.161 (16.1 percent). This is the buyer's risk. The operating characteristic (OC) curve is constructed by calculating the probability of accepting the lot for several reasonable values of fraction defective, in addition to those needed to calculate α and β. The OC curve for the example just presented is shown in Figure 13.

The seller's risk is high relative to the buyer's risk. This problem can be remedied by including dual decision criteria, as discussed in the next section.

Double specification limits, dual decision criteria

Double decision criteria can be implemented with double specification limits in a similar manner that they were implemented with single specification limits. Double decision criteria permit the inclusion of pay adjustment factors. The following example demonstrates the use of double decision criteria for quality assurance of binder content for asphalt concrete.

Example. Similar to the previous problem, six extraction tests are performed for each lot of asphalt concrete mixture (n=6). The limits and the fraction nonconforming criteria for AQL, c, and UQL remain unchanged from the previous problem. The new fraction nonconforming criterion, which is the rejection limit, r, is set at 0.125. Since the original limits and criteria have not changed, the checks performed in the previous problems hold true for the current problem. The checks included one for specification reasonableness and a second for ensuring that risk calculations could be handled as one-tail tests.

The buyer's risk remains as the probability that the calculated fraction defective will be less than 0.075 (c) if the true (mean) fraction defective is 0.15 (UQL). The seller's risk is now calculated as the probability that the fraction defective will exceed 0.125 (r) if the true (mean) fraction defective is 0.05 (AQL). The standard normal value for the rejection number (r) is shown below.

$$z_r = z_{0.125}(one\text{-}tail) = 1.150 \tag{68}$$

The buyer's risk (β), which remains unchanged from the previous problem, is 0.161 (16.1 percent) The seller's risk (α) changes with the addition of the rejection number (r). The standard normal variate for (α) is calculated as follows.

$$z_\alpha = \frac{z_{AQL} - z_r}{\frac{1}{\sqrt{6}}} = \frac{1.645 - 1.150}{\frac{1}{\sqrt{6}}} = 1.212 \tag{69}$$

The seller's risk is calculated as the probability of the normal variate exceeding 1.212, which is 0.113 (11.3 percent). The relative magnitudes between the buyer's risk and the seller's risk are now more appropriate than they were in the previous problem. The operating characteristic (OC) curve is constructed by calculating the probability of accepting the lot for several reasonable values of fraction nonconforming, in addition to those needed to calculate α and β. The OC curves for the example just presented are shown in Figure 14. Similar to the previous problem that included dual criteria, the OC curve consists of two curves. The area between the two curves is handled with pay adjustments as will be described in the next section.

Calculating Fraction Nonconforming and Adjusting Payment

As presented in the section titled "Reference Distributions," fraction nonconforming for sample data will be calculated with the quality index statistic, Q. This section will address the calculation of fractions of nonconforming material for dual decision criteria cases only. These cases, which will be consistent with problems introduced previously, will permit descriptions of how to incorporate payment adjustments.

Single specification limit, dual decision criteria

Example. Suppose four density tests are performed for a lot of compacted subgrade material (n=4). The lower limit (LL) of acceptability for dry density is specified to be 90 percent of maximum, as determined by modified Proctor procedures. The AQL, c, r, and UQL, in terms of fraction defective, are 0.05, 0.10, 0.15, and 0.20, respectively. If the average density is 95 percent and the standard deviation is 3.5 percent for a sample of four tests, Q can be used to estimate the fraction nonconforming in the particular lot.

$$Q(lower) = Q_L = \frac{\bar{y} - LL}{s} = \frac{95 - 90}{3.5} = 1.43 \quad (70)$$

$$P(Q > 1.43) = 0.023 \quad (71)$$

The probability of obtaining Q greater than 1.43 can be obtained from Table A3 (Appendix A) or from a surrogate beta distribution, as shown in Appendix B. In this example, the fraction of nonconforming material is estimated as 0.023, which is less than both AQL (0.05) and c (0.10). Payment adjustment schedules use c as the demarcation of 100 percent pay. Since our estimate for fraction nonconforming is less than c, the seller would receive 100 percent payment for this lot.

As another example, assume the average density is 95 percent and the standard deviation is 4.5, as determined from a sample of four tests.

$$Q(lower) = Q_L = \frac{95 - 90}{4.5} = 1.11 \quad (72)$$

$$P(Q > 1.11) = 0.130 \quad (73)$$

In this example, the fraction nonconforming is estimated as 0.130, which is between c (0.10) and r (0.15). The lot is not rejected because the fraction nonconforming is less than r. However, the lot does not receive 100 percent payment because the fraction defective is greater than c. The lot is accepted at reduced payment. If the fraction nonconforming had been estimated as any value greater than 0.15, the lot would have been rejected.

Payment reductions for continuous variables are often based on continuous, linear scales between c and r. For example, the top of the scale (c) could be set at 100 percent payment. The bottom of the scale (r) should be set at a value that reflects the added costs to the buyer, which are caused by the poor quality product. For the previous example, one must decide on the costs to the buyer that result from having 15 percent (r) of subgrade soil below the lower limit of 90 percent for relative density. Added costs could include susceptibility of a pavement structure to permanent deformation, due to densification of the soil and/or increased susceptibility to softening under the influence of moisture. These estimates of added costs are rarely strict, concise calculations. They often are merely based on reasonable assumptions and logical thought processes.

For the previous example, the specification could be written so that the payment at a fraction nonconforming equal to r (0.15) is 75 percent. If the payment varies linearly between r and c, the payment for our calculated fraction defective (0.130) would proceed as follows.

$$Payment = 100 - \frac{0.13 - 0.10}{0.15 - 0.10} \times 25 = 85 \ percent \tag{74}$$

Double specification limits, dual decision criteria

Example. Recall that the binder content of asphalt concrete was to be tested by six extractions per lot of mixture (n=6). The lower limit (LL) of acceptability for binder content was specified to be 5.0 percent, while the upper limit (UL) of acceptability was specified to be 7.0 percent. The fraction nonconforming criteria for AQL, c, r, and UQL were 0.05, 0.075, 0.125, and 0.15, respectively. Assume that samples from a lot provided an average sample binder content of 6.3 percent and a standard deviation of 0.80 percent. Estimates for nonconforming material can be obtained with Q, but they must include both portions below LL and above UL.

$$Q_L = \frac{\bar{y} - LL}{s} = \frac{6.3 - 5.0}{0.80} = 1.63 \tag{75}$$

$$Q_U = \frac{UL - \bar{y}}{s} = \frac{7.0 - 6.3}{0.80} = 0.88 \tag{76}$$

$$P(Q > 1.63) + P(Q > 0.88) = 0.028 + 0.197 = 0.225 \tag{77}$$

The total estimated fraction nonconforming is 0.225, which is greater than r (0.125). Therefore, the lot is rejected. Notice that the standard deviation of the sampled material is 0.80 percent. This is a high value relative to that which is ordinarily encountered for extracted asphalt cement content.

As another example, assume the same average binder content of 6.3 percent, but suppose that the seller has reduced the standard deviation to 0.55 percent.

$$Q_L = \frac{\bar{y} - LL}{s} = \frac{6.3 - 5.0}{0.55} = 2.36 \tag{78}$$

$$Q_U = \frac{UL - \bar{y}}{s} = \frac{7.0 - 6.3}{0.55} = 1.27 \tag{79}$$

$$P(Q > 2.36) + P(Q > 1.27) = 0.000 + 0.094 = 0.094 \tag{80}$$

The total fraction nonconforming is estimated as 0.094, which is between c (0.075) and r (0.125). This lot would be accepted, but at reduced payment.

If the payment schedule is assumed to be linear between 100 percent at c and 50 percent at r, the payment for this lot would be calculated as shown below.

$$Payment = 100 - \frac{0.094 - 0.075}{0.125 - 0.075} \times 50 = 81 \; percent \tag{81}$$

The percent payment corresponding to r is lower for this problem than it was for the problem involving soil compaction (50 percent versus 75 percent). A reason for this could be that during the development of the specification, deviations in asphalt concrete binder contents were judged to be more expensive to the buyer than deviations in the relative density of subgrade soil.

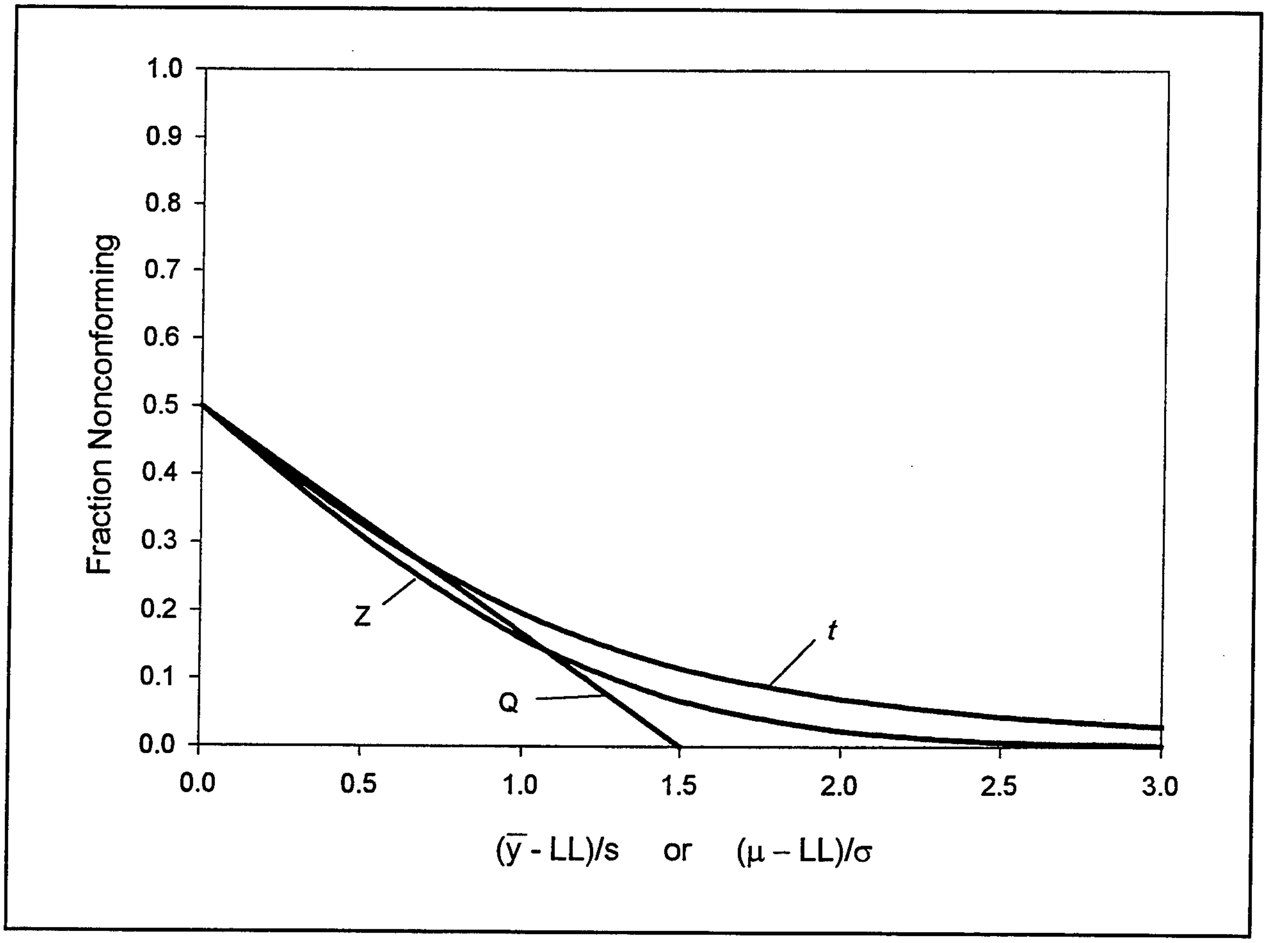

Figure 5. Comparison of Q, t, and Z calculations (sample size = 4)

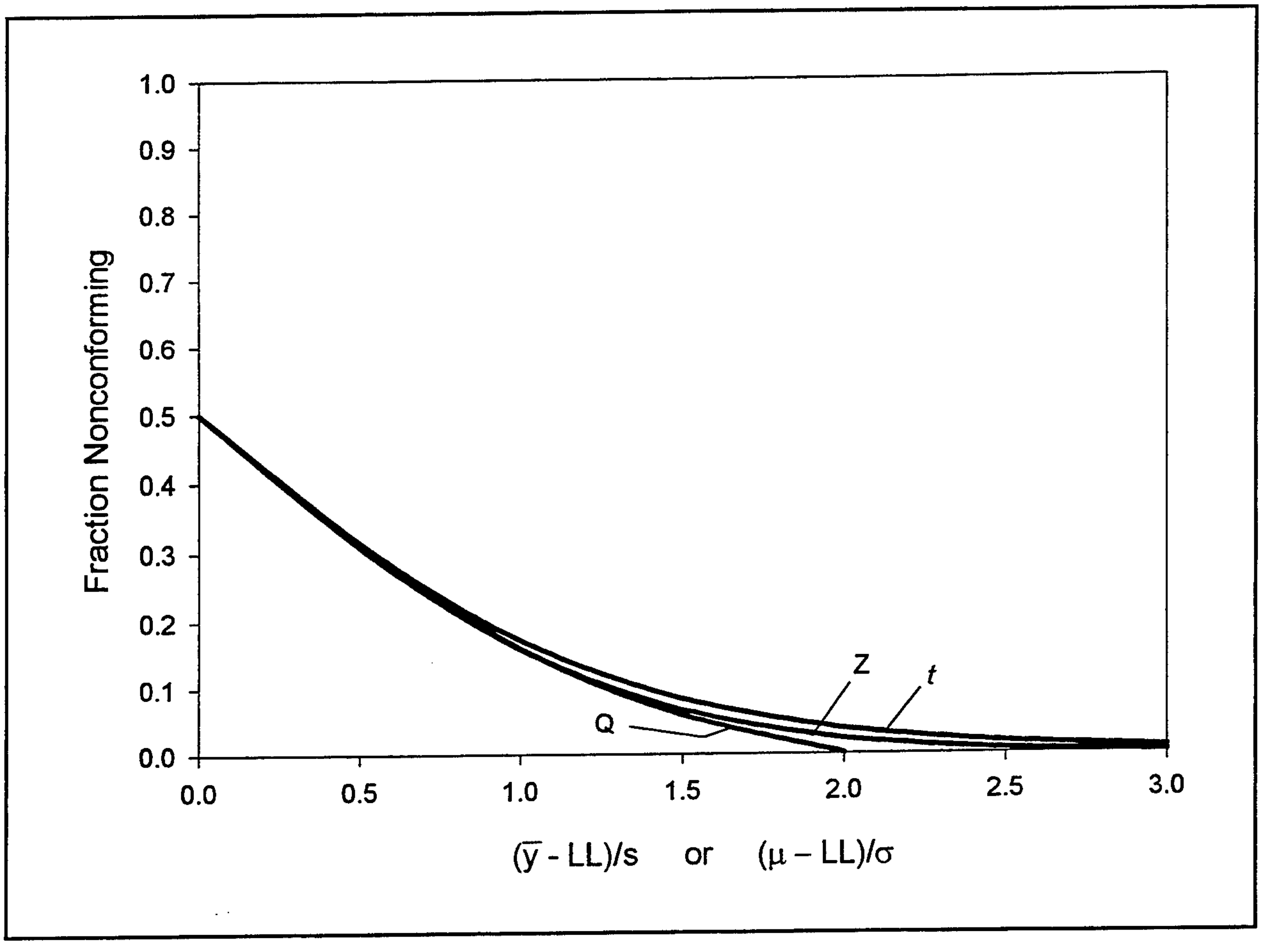

Figure 6. Comparison of Q, t, and Z calculations (sample size = 10)

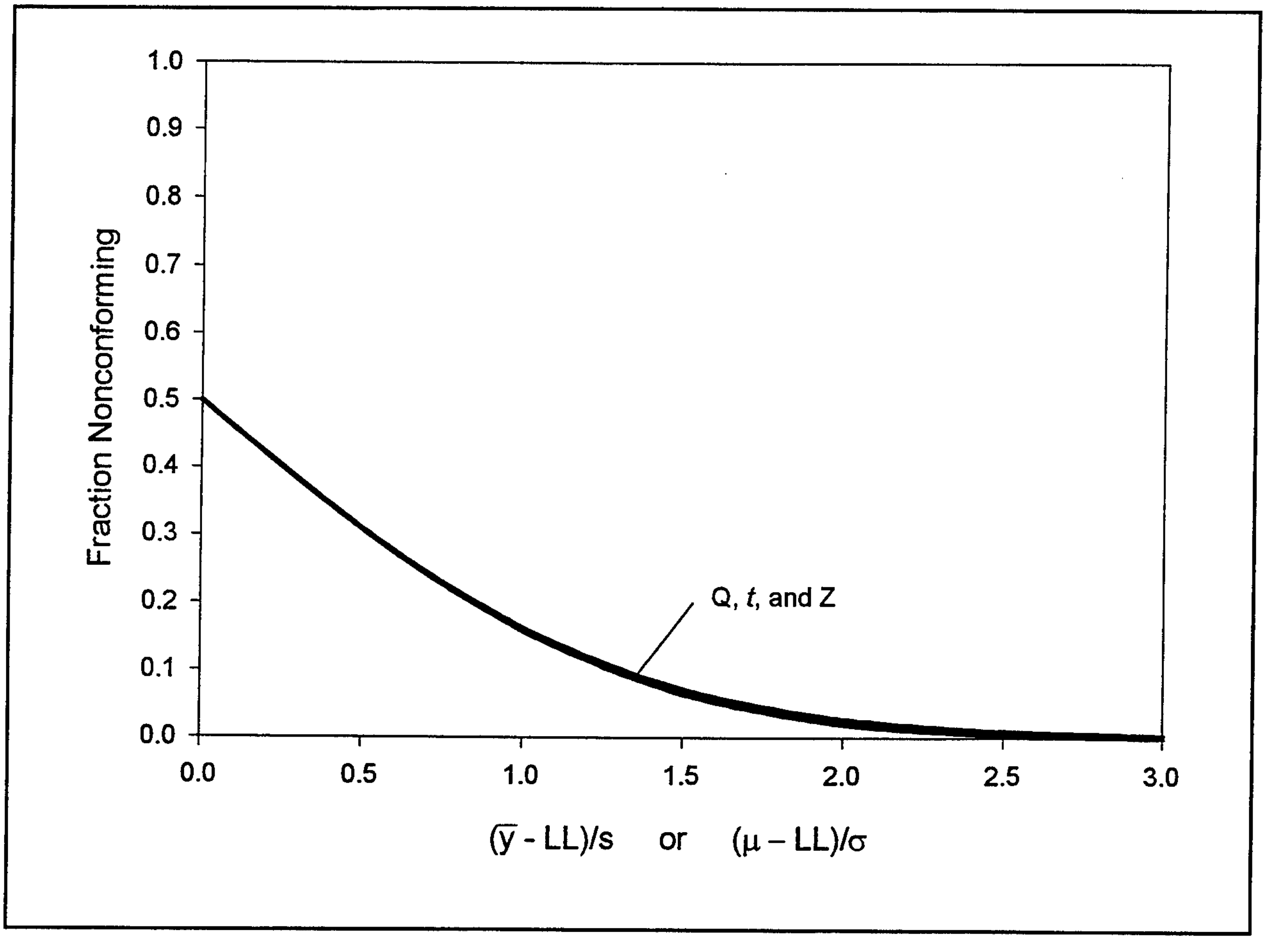

Figure 7. Comparison of Q, t, and Z calculations (sample size = 30)

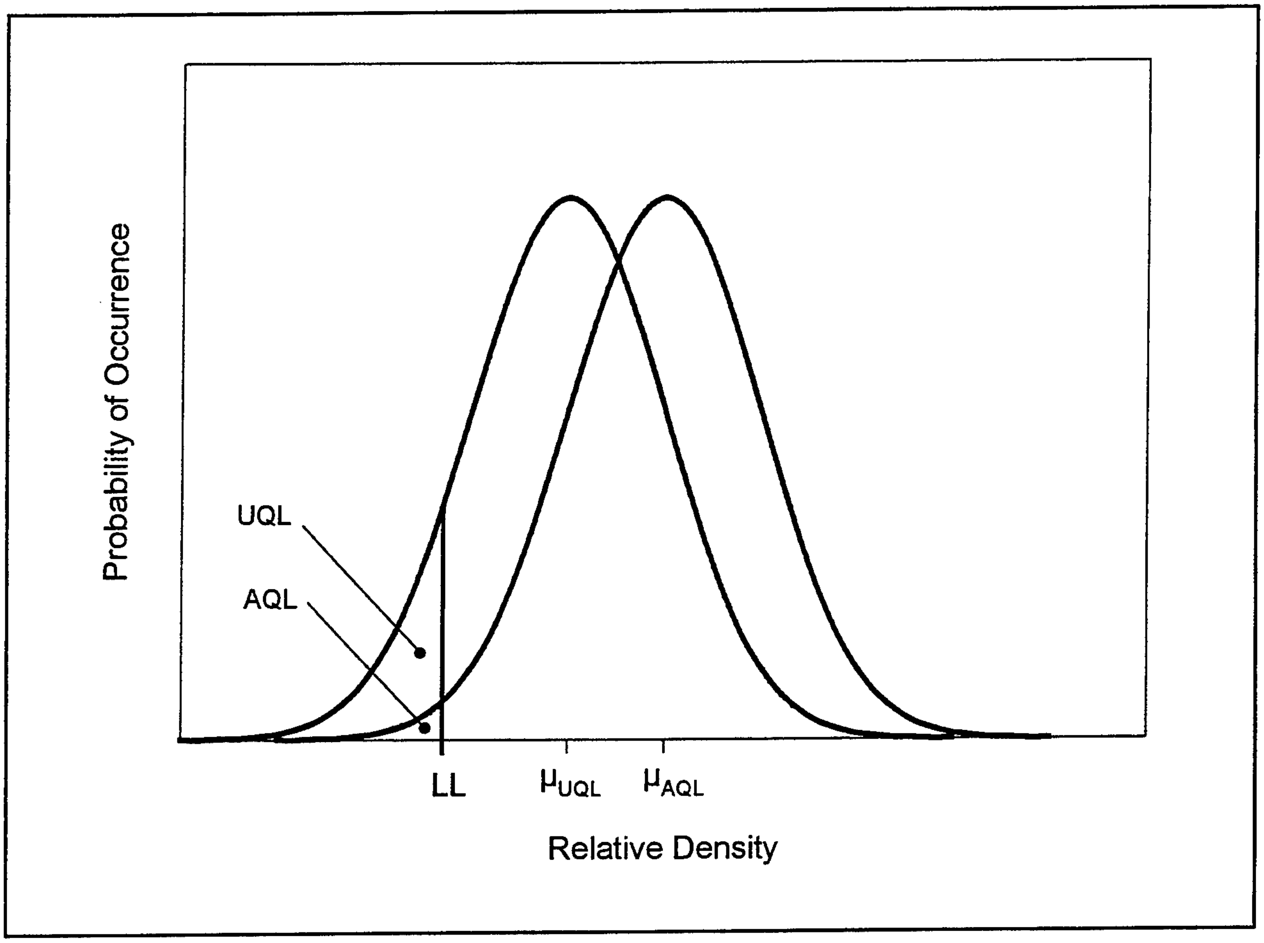

Figure 8. Relationships between limits and criteria

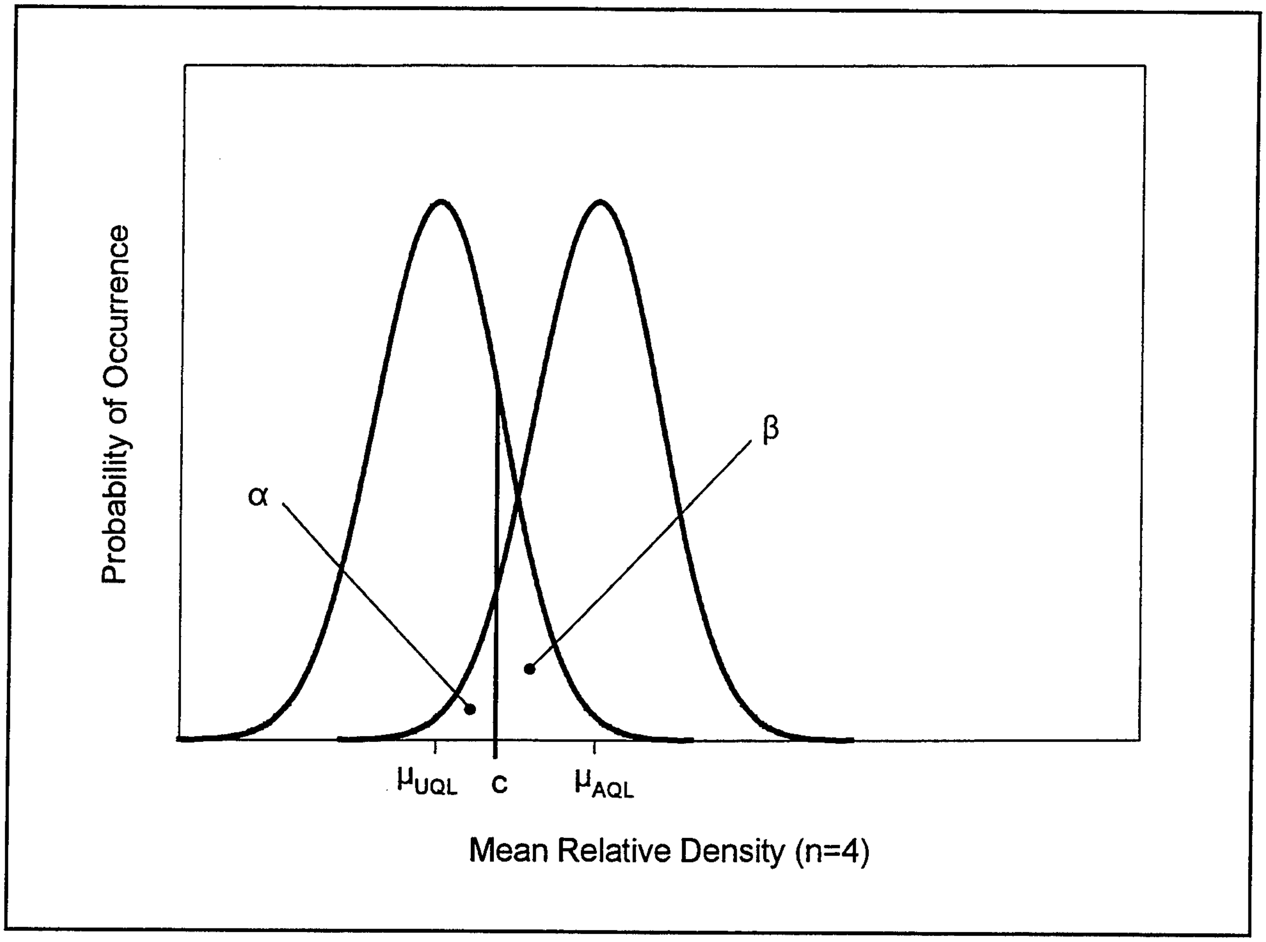

Figure 9. Seller's risk (α) and buyer's risk (β)

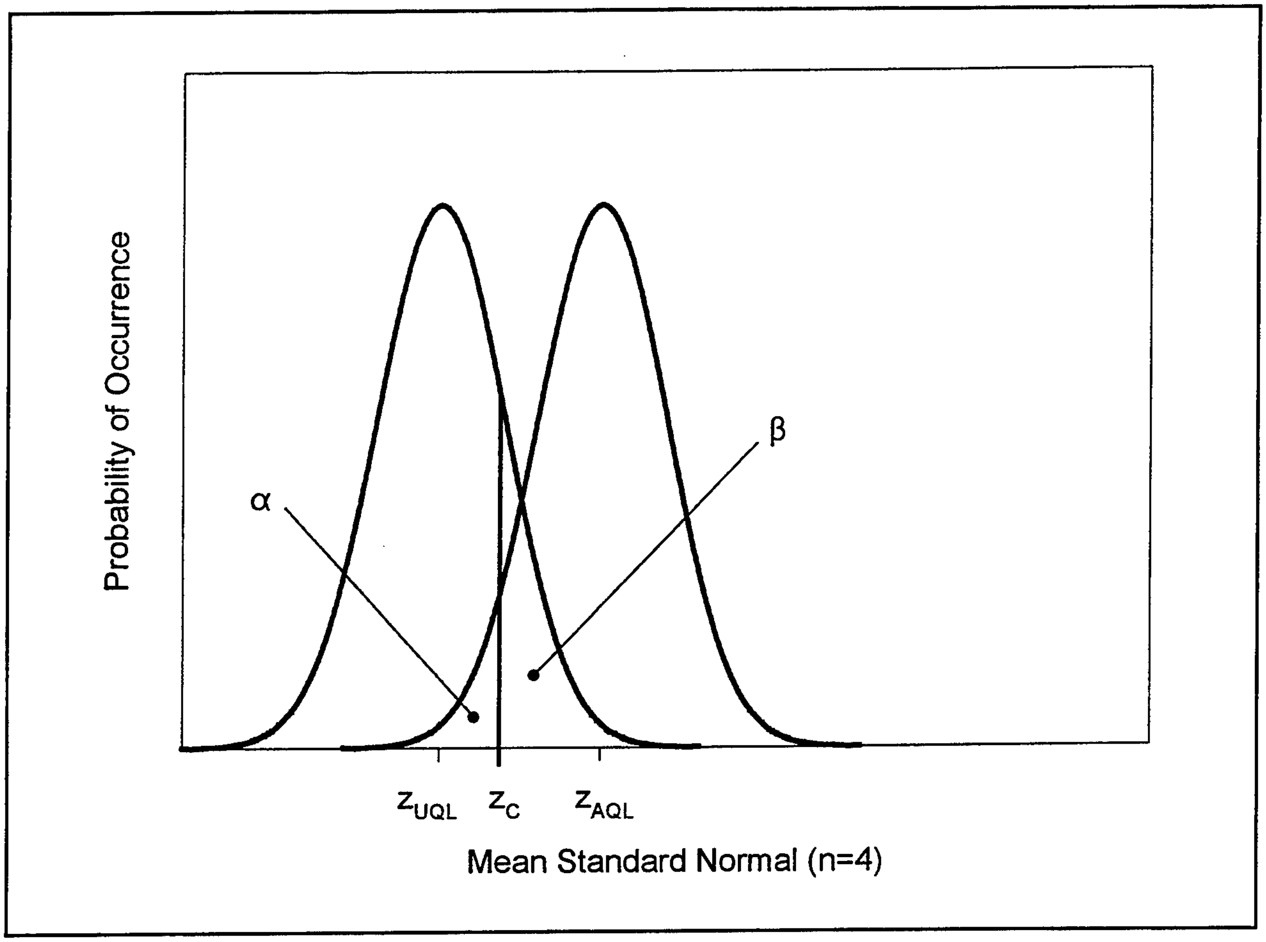

Figure 10. Determining risks by Z-statistic means

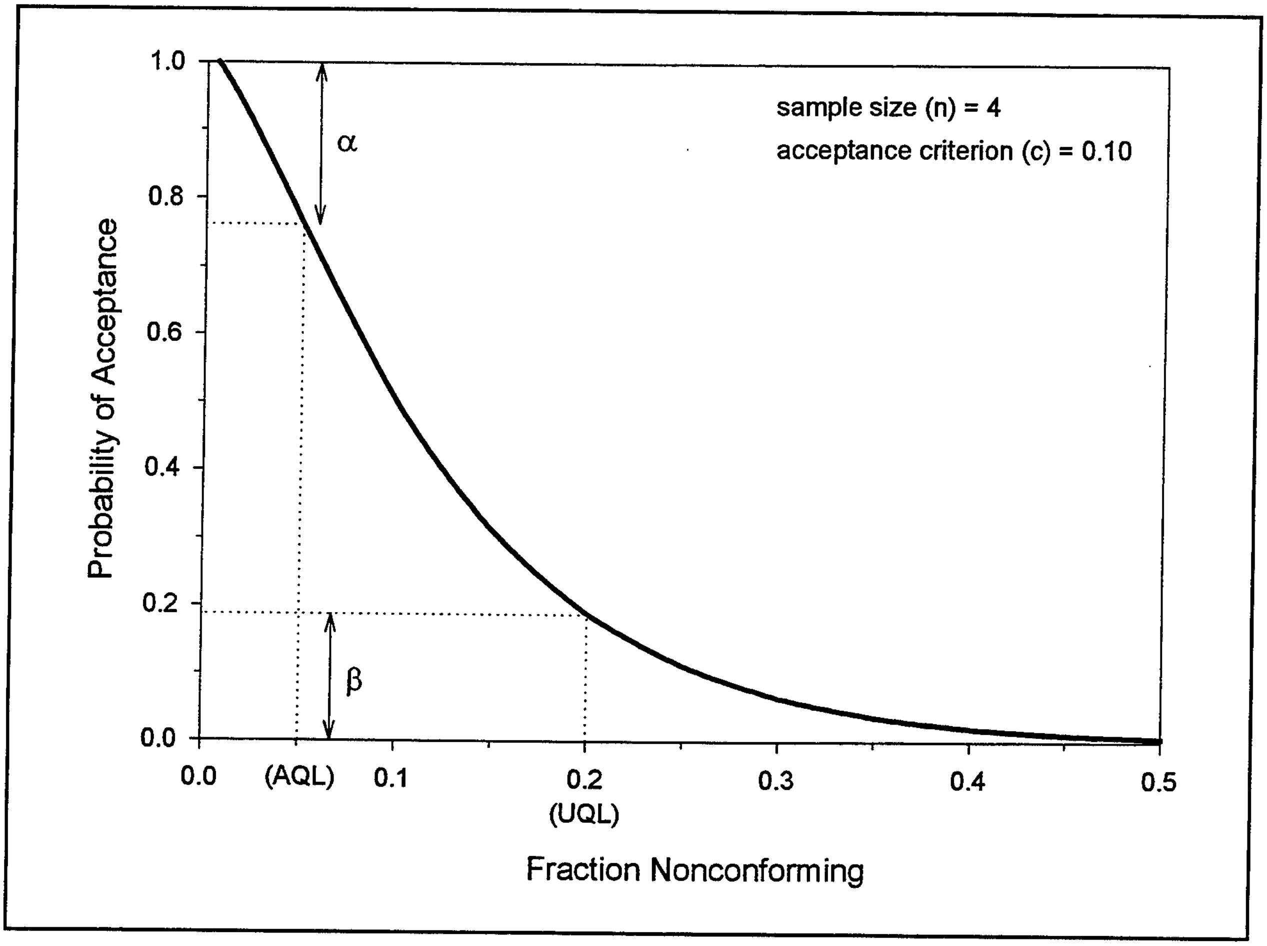

Figure 11. OC curve for single limit, single criterion

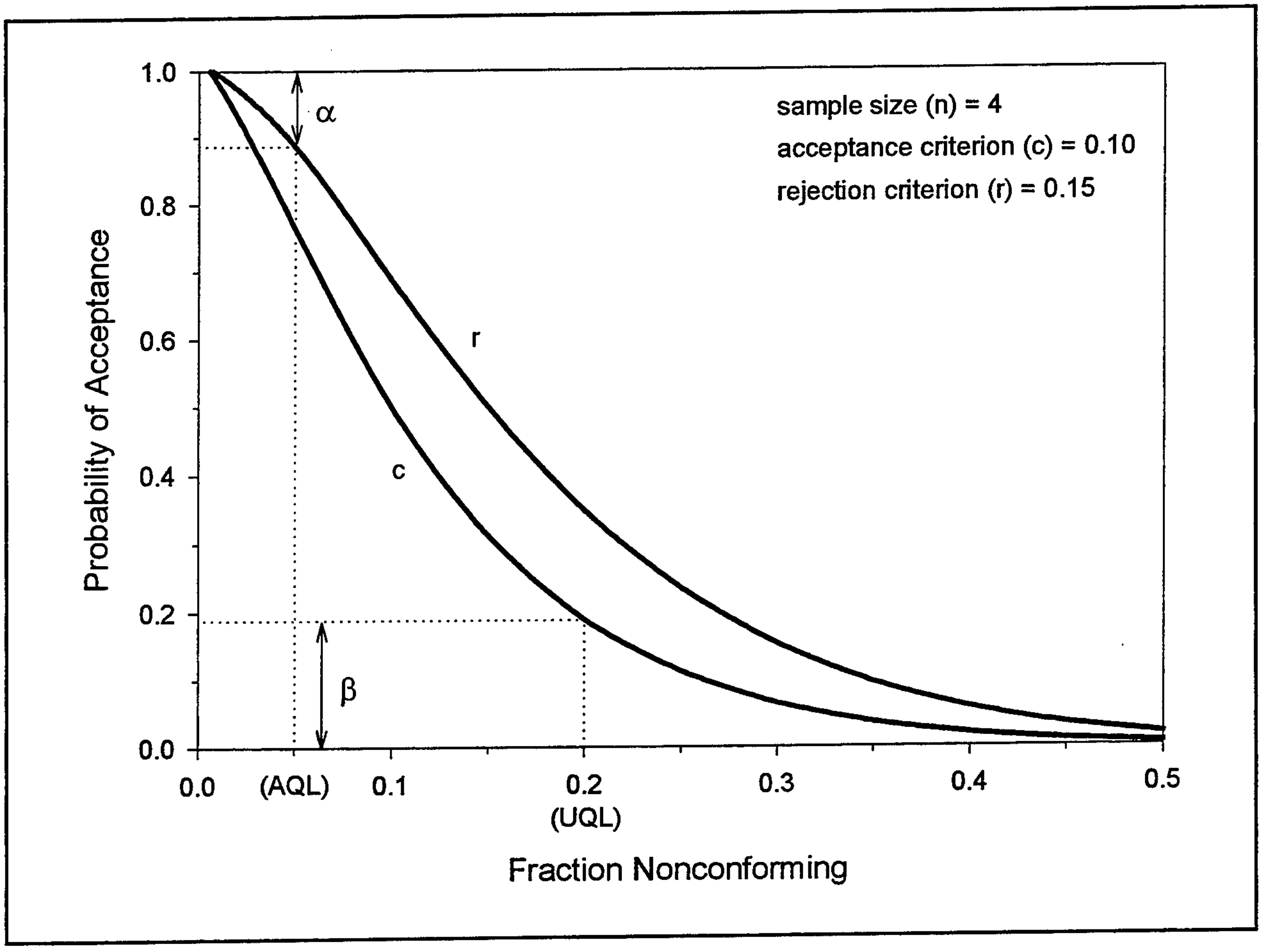

Figure 12. OC curve for single limit, dual criteria

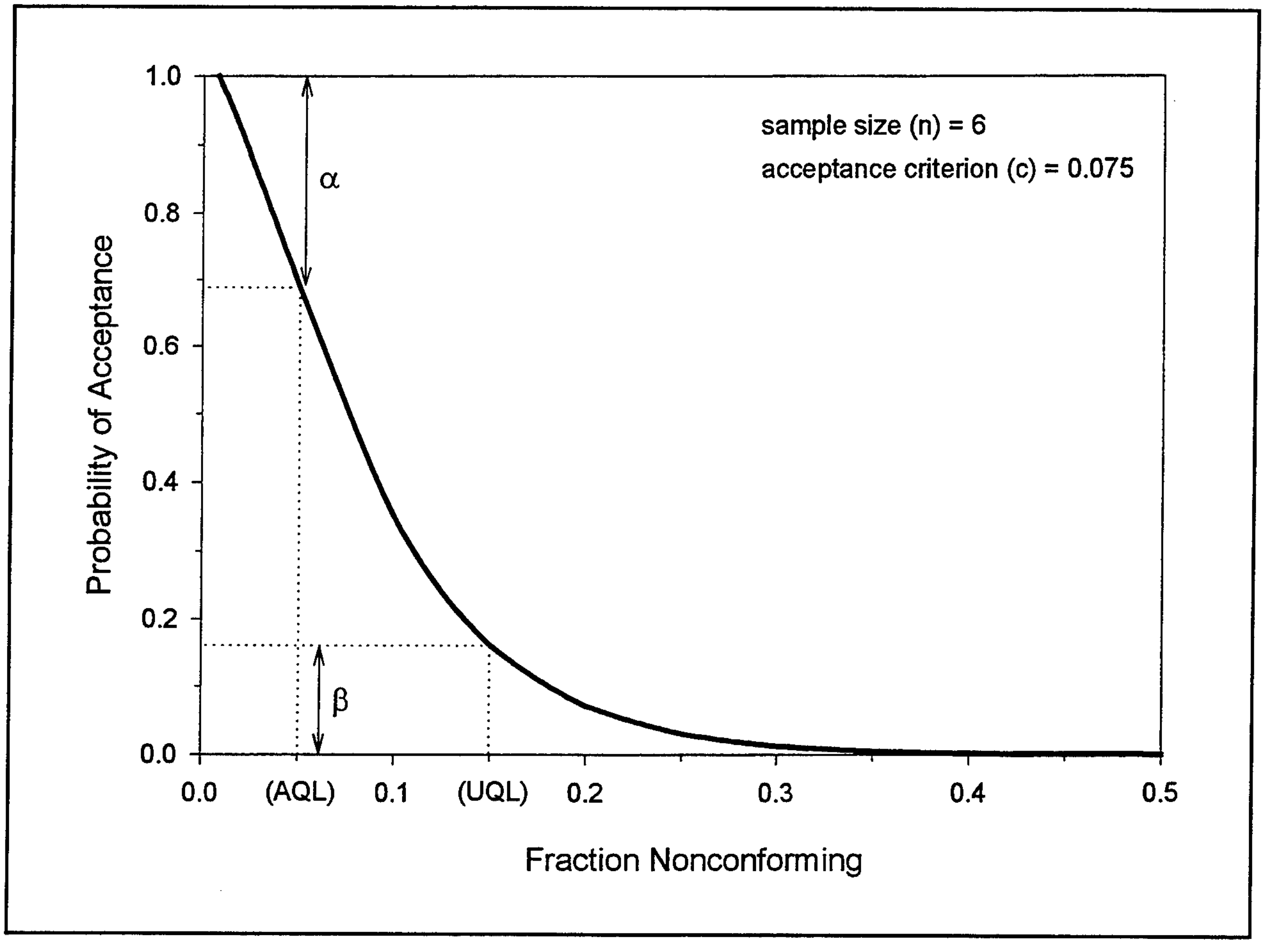

Figure 13. OC curve for double limits, single criterion

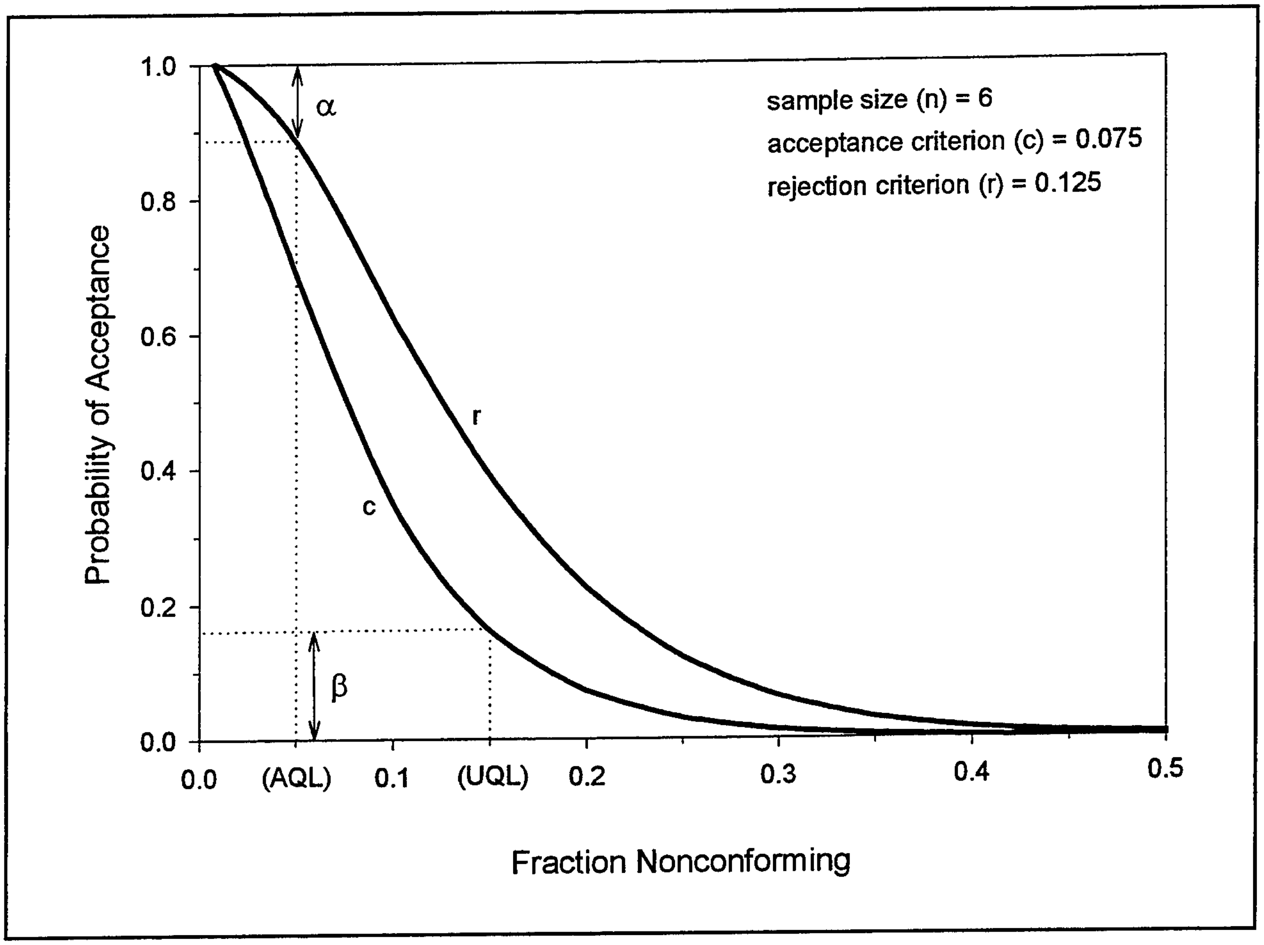

Figure 14. OC curve for double limits, dual criteria

6 Current Practices

This chapter presents the current practices for quality assurance of asphalt concrete for pavement structures. The agencies included in this chapter are the Federal Highway Administration (FHWA), the Federal Aviation Administration (FAA), and the U.S. Army Corps of Engineers (USACE). Discussions address only dense-graded asphalt concrete materials.

FHWA

The FHWA quality assurance plan for asphalt concrete addresses four material characteristics: asphalt cement content, aggregate gradation, field density, and smoothness (FHWA 1992). For each characteristic, the FHWA estimates the percentage of a lot that is outside specification limits, or percent defective (PD). Percent defective is synonymous with fraction nonconforming, as presented in Chapter 5. The statistical technique used assumes variability to be unknown. To implement this method, the FHWA defines acceptable quality level (AQL) as the highest percentage of work outside the specification limits that is considered acceptable for payment at the full contract price. They define two acceptance categories: Category I, based on an AQL of 5 percent, and Category II, based on an AQL of 10 percent. In both cases, the Contractor's risk is set at 5 percent. This risk is the probability that work produced at AQL is rejected or accepted at a reduced contract price.

The FHWA statistical evaluation of data requires five or more samples per lot of material. A lot is defined as a discrete quantity of work to which the statistical acceptance procedure is applied. A lot normally represents the total quantity of work produced. However, more than one lot may occur in a project if changes occur in one or more of the following: target values, material sources, or job-mix formula. The FHWA does not divide lots into a certain number of sublots. They recommend setting a sampling rate for each material characteristic. These rates and details of sampling location are established by the individual state transportation agencies.

The percent of a lot outside of specification limits is estimated in two parts: P_U represents the percent of material falling outside of an upper specification limit and P_L represents the percent of material falling outside of a lower specification limit. Estimation of P_U and P_L requires the calculation of upper and lower quality indices: Q_U and Q_L, respectively. These indices are calculated in

the manner shown in Chapter 5 of this report and they are compared to a table in the FHWA specification that is similar to Table A4 included in this report.

Pay factors are calculated for each of the material quality characteristics included in the quality assurance plan: asphalt cement content, aggregate gradation, field density, and smoothness. Payment for material in a lot is determined by multiplying the contract unit bid price by a "lot pay factor," which is the lowest pay factor out of the material quality characteristics. Pay factor calculations are based on $P_U + P_L$, sample size, and acceptance category (AQL equal to 5 percent or 10 percent). A lot is rejected if any of the material pay factor components (for either of the material quality characteristics) falls into the "reject" portion of Table 1.

When all quality characteristics are Category I, the lot pay factor is based on the lowest single pay factor for any of the quality characteristics. The maximum obtainable pay factor is 1.05 with a minimum of 8 test values. When all quality characteristics are Category II, the lot pay factor is again based on the lowest single pay factor for any of the quality characteristics. The maximum obtainable pay factor is 1.00 with a minimum of 5 test values. When quality characteristics for a lot include both Category I and II, the lot pay factor is based on the following:

a. When all Category II quality characteristics are 1.00, the lot payment is based on the lowest single pay factor for all Category I characteristics. The maximum obtainable pay factor is 1.05 with a minimum of 8 test values.

b. When any Category II quality characteristic is less than 1.00, the lot payment is based on the lowest single pay factor for any quality characteristic. The maximum obtainable pay factor is 1.00 with a minimum of 5 test values.

If the sampling rate defined by a state agency for a given project would result in fewer than 8 samples, a Contractor may submit a written request to increase the sampling rate to produce 8 or more samples. The advantage of the larger sample size is the chance to earn pay factors greater than 1.00.

The upper and lower specification limits for asphalt cement content are the approved job-mix formula target value ± 0.5 percent. The upper and lower specification limits for aggregate gradation are the job-mix formula target values plus or minus the allowable deviations shown in Table 2. The lower limit for core samples cut from the compacted pavement is 90 percent of the maximum density determined according to AASHTO T 209 (AASHTO 1995) as part of the job-mix formula evaluation.

Smoothness of the final surface course is judged with a California-type profilograph. Measurements are taken parallel to the centerline, within 3 days of each day's paving. Each lane is measured in either the left or right wheel path (as directed). Measurements are not taken within 8 m (25 ft) of any neighboring structure. A profile index is calculated for each 0.1 km (0.1 mile) length

of roadway. Upper specification limits and defective limits are shown in Table 3. Defective limits are used to define areas that must be corrected.

The profilograph measurements are supplemented with straightedge measurements to find defective areas. A 3 m (10 ft) straightedge is used at right angles and parallel to the centerline at designated sites. A defective area is an area with surface deviations in excess of 5 mm (0.19 in.) between any 2 contacts of the straightedge with the surface. When defective areas are corrected, final pay factors are calculated using the new materials and/or new smoothness achieved in the corrected areas.

FAA

The FAA statistical evaluation method is based on estimating the percent of a lot that is within specification limits (percent within limits, PWL) (FAA 1994). This method is similar to the FHWA method in that quality indices are calculated using sample estimates for the mean and standard deviation, as shown in Chapter 5 of this report. According to FAA procedures, Q_L and Q_U values are entered into a table similar to Table A3 (Appendix A) to obtain percentages of material (P_L and P_U) outside of specification limits. The percentage of material within limits is then calculated as

$$PWL = (P_L + P_U) - 100 \tag{82}$$

where

P_L = percent within lower limit

P_U = percent within upper limit

According to the FAA specification, a lot of plant-produced asphalt concrete will consist of:

a. One day's production not to exceed 1,814,000 kg (2000 tons).

b. One half day's production where a day's production is expected to consist of 1,814,000 kg to 3,628,000 kg (2,000 tons to 4,000 tons).

c. Similar subdivisions for masses greater than 3,628,000 kg (4,000 tons).

Each lot consists of four equal sublots and samples from each sublot are selected randomly. Sampling is performed on materials deposited into trucks at the plant or from trucks at the job site. Samples of hot-mix are obtained in accordance with ASTM D 3665 and portions of these samples are compacted in accordance with ASTM D 1559, with the same number of blows per face as that used for the mixture designs. Each sublot sample increment includes a set of three compacted laboratory specimens. These specimens are measured for bulk specific gravity in accordance with ASTM D 2726 or D 1118, whichever is applicable. The specimens are then tested for Marshall stability and flow in

accordance with ASTM D 1559. Air voids determination, in accordance with ASTM D 3203, requires the theoretical maximum specific gravity. This value is measured twice for each lot in accordance with ASTM D 2041, Type C or D container. Samples for this test are obtained randomly in accordance with ASTM D 3665.

Material placed in the field is evaluated for mat and joint density on a lot basis. The lot size is the same as that used for sampling hot-mix material. The lot is divided into four equal-size sublots and one core of finished, compacted material is obtained for each sublot. Core locations are selected randomly in accordance with procedures in ASTM D 3665. Cores are not taken closer than one foot of a transverse or longitudinal joint. For joint density, the lot size is considered as the total length of longitudinal joints constructed by a lot of material and the lot is divided into four equal-size sublots. One core is obtained for each sublot of joint length.

Acceptance testing of bituminous mixtures addresses eight characteristics: stability, flow, air voids, mat density, joint density, thickness, smoothness, and grade. Specification limits for stability, flow, air voids, and density are shown in Table 4 for two mixture classes.

If the PWL for stability or flow for a lot, relative to the limits shown in the table, equals or exceeds 90 percent, the lot is acceptable. If the PWL is less than 90 percent, the Contractor must determine the cause and take corrective action. If the PWL is less than 80 percent, the Contractor must stop production and make adjustments to the mix. There are no pay adjustments based on stability and flow.

If the PWL for mat density and air voids for a lot equals or exceeds 90 percent, the lot is acceptable and receives full contract price. If the PWL is less than 90 percent, pay is adjusted according to Table 5. Payment is calculated for both mat density and air voids, and final payment is based on the lower of the two values.

Similar to stability and flow, joint density does not affect payment. If the PWL for joint density equals or exceeds 90 percent, the lot is acceptable. If the PWL is less than 90 percent, the Contractor must evaluate the method of compacting joints. If the PWL is less than 80 percent, the Contractor must stop production until the reason for poor compaction can be determined.

Thickness is evaluated for compliance by the Engineer, however no rules are written concerning allowable deviations or pay adjustments. Thicknesses are measured from the cores taken for field density measurements.

Smoothness measurements are obtained with a 3.6 m (12 ft) straightedge. The upper limit for deviation is 6.2 mm (1/4 in.) for finished pavement surfaces. Grade is judged by measuring elevations. The finished surface of the pavement shall not vary from the gradeline elevations shown on the plans by more than 12.7 mm (1/2 in.). The Engineer can specify a lot size for each of these measurements different than that previously defined, but a minimum of 1,650 m^2 (2,000 yd^2) is recommended. Straightedge measurements are made

perpendicular and parallel to the centerline at distances not to exceed 15.2 m (50 ft). The finished grade of each lot will be determined by running levels at intervals of 15.2 m (50 ft) or less longitudinally and transversely to determine the elevation of the completed pavement. When more than 15 percent of either set of measurements within a lot exceed the specified tolerance, the Contractor must remove the deficient area and replace with new material. Sufficient material shall be removed to allow at least one inch of asphalt concrete to be placed. Skin patching shall not be permitted. High points may be ground off.

Resampling a lot of pavement for mat density is allowed by the FAA if the Contractor makes a request in writing within 48 hours of receiving the written test results from the Engineer. The cost for resampling and retesting is assumed by the Contractor. Resampling follows similar procedures as the original sampling and testing. Only one resampling is permitted for each lot. The results from resampling are combined with the original sample to calculate a redefined PWL. The redefined PWL is used to calculate payment for the resampled lot, in accordance with Table 5. A potential outlier can be tested in accordance with ASTM E 178, using a significance level of 5 percent.

USACE

The USACE applies separate guide specifications (CEGS) for heavy-duty asphalt concrete and asphalt concrete for roads and streets: CEGS 02556 (USACE 1991) and CEGS 02551 (USACE 1989), respectively. The CEGS for heavy-duty asphalt concrete addresses mixtures designed with 75 Marshall hammer blows, while the CEGS for roads and streets addresses mixtures designed with 50 Marshall hammer blows. Both guide specifications are included in this review, so their similarities and differences will be apparent. Acceptance testing in these specifications includes both the asphalt concrete mixtures and the finished pavement surface. Asphalt concrete mixtures are tested for laboratory density, aggregate gradation, and asphalt cement content. Finished pavement surfaces are tested for field density, grade, and surface smoothness.

Percent defective or percent within limits concepts are not currently used in the USACE pavement specifications. The statistical method for handling asphalt cement content and aggregate gradation data is based on calculating mean absolute deviations.

$$Mean\ Absolute\ Deviation = \frac{\sum_{i=1}^{n} |y_i - y_{jmf}|}{N} \tag{83}$$

where

y_i = individual observations

y_{jmf} = value specified in the job-mix formula

N = number of observations in the lot

Testing for acceptability of work is generally performed by the Government. However, at the discretion of the Government, the Contractor's laboratory may perform any of the acceptance testing.

The lot size can be specified on the basis of time or amount of production. If the lot size is based on time, 8 hr (1 day) of production is usually appropriate. If the lot size is based on amount of production, the amount selected should be approximately equal to the amount of material produced in a single day. For asphalt concrete, this value should not exceed 1800 metric tons (2000 tons).

In order to evaluate aggregate gradation, asphalt cement content, laboratory density, and field density, each lot is divided into four equal sublots. Grade and surface smoothness determinations are made on the lot as a whole.

For field density determination, a random core sample will be obtained from both the mat and the longitudinal joint of each sublot. Each sample should include at least 1250 g of the pavement layer that is to be tested. To meet this mass requirement, more than one core will be needed at each sample location if the pavement layer thickness is less than approximately 60 mm. For determination of asphalt cement content, aggregate gradation, and laboratory density, a random sample of asphalt concrete will be obtained from a single truck for each sublot. The specification emphasizes that the sample will be "truly random, not haphazard, using commonly recognized methods of assuring randomness, employing randomizing tables or computer programs."

When a lot of material fails to meet the specification requirements, that lot shall be removed and replaced or accepted at a reduced price. To calculate the reduced payment, the lowest computed percent payment determined for any pavement characteristic (i.e gradation, asphalt content, density, grade, and smoothness), as discussed below, is multiplied by the bid price and the quantity of bituminous mixture placed in the lot. The Contracting Officer reserves the right to direct additional samples and tests for any area which appears to deviate from the specification requirements. Testing in these areas will be in addition to the lot testing, and the requirements for these areas will be the same as those for a lot. Currently, no guidance is provided as to whether these tests are considered as a separate lot or whether they are combined with other data.

Acceptability calculations for asphalt cement content and aggregate gradation are based on comparing sample data and job-mix formula data, using mean absolute deviation. The mean deviation calculated from the four asphalt cement content determinations (one from each sublot) is compared with Table 6 to determine percent payment. The asphalt cement content test results for each lot will be reported within 24 hr of construction.

Pay adjustments for aggregate gradation are based on absolute deviations between sample gradations and the job-mix formula gradation. The clean aggregate obtained from the extraction test for each sample is sieved to determine percent passing for the following sieves: 25.4 mm, 19.0 mm, 12.5 mm,

9.5 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.60 mm, 0.30 mm, 0.15 mm, and 0.075 mm. For each sieve size, the absolute deviation between measured percent passing and the job-mix formula percent passing is calculated. The mean absolute deviation for each sieve size is obtained by averaging the test results for the four samples (four sublots per lot). The mean deviation for each sieve size is compared to the pay adjustments shown in Table 7. The overall percent payment based on aggregate gradation will be the lowest value determined from Table 7. All tests for aggregate gradation will be completed and reported within 24 hr after construction of a lot.

Pay adjustments for density are based on comparisons between field densities (both mat and joint) and laboratory densities. The mat and joint field densities are obtained from core samples, while the laboratory density is obtained by compacting loose asphalt concrete that has been sampled from trucks (or other appropriate location). Laboratory compaction should be similar to that used for the mixture design, should be completed within 2 hr of the time the mixture is loaded into trucks, and should be performed before the temperature of the mixture drops below 120°C (250°F). Each sublot sample that is to be used for the laboratory compactions will be divided into three subsamples. A single Marshall-size specimen will be compacted from each of the three subsamples. In addition to determining density for all twelve specimens for each lot (3 subsamples for each of 4 sublots), Marshall stability, Marshall flow, total voids, and voids filled, will be determined for one specimen from each sublot. Currently, the specification does not advise on how to use these data.

The overall averages for mat and joint densities can be expressed as percentages relative to the overall average for laboratory density. These percentages can then be compared to the values in Table 8 in order to determine pay adjustment percentages. Pay adjustments for mat and joint densities are compared and the most severe adjustment is used. The comparison requires conversion of percent payment to pay deduction percentages by subtracting percent payment from 100. The joint density deduction is then scaled according to the area of pavement accounted for by joints. To scale joint density, its deduction percentage is multiplied by the ratio of joint strip area to the total mat area. Longitudinal joint strips are considered to be 10 ft wide in any case where two adjacent pavement lanes are placed. The rule of 10 ft applies when new pavement lies on both sides of the longitudinal joint and when new pavement is placed against an existing pavement. The largest calculated density deduction, between mat and joint, is then subtracted from 100 percent to obtain an overall percent payment for asphalt concrete field density. All density results for a lot will be completed and reported within 24 hr after the construction of that lot.

When the Contracting Officer considers it necessary to take additional samples for density, sampling will be performed in groups of four (one core for each sublot). The percent payment shall be determined for each additional group of four samples and averaged with the percent payment for the original group to determine the final percent payment.

The finished surface of the pavement will be tested for conformance with grade and smoothness requirements. The finished grade of each pavement will be determined by running lines of levels at intervals of 8 m (25 ft) or less

longitudinally and transversely to determine the elevation of the completed pavement. The grade of the completed surface shall not deviate more than 15 mm (0.05 ft) from the plan grade. For aircraft traffic areas, this requirement may be reduced to 9 mm (0.03 ft). When more than 5 percent of all measurements made within a lot are outside the specified tolerances, the computed percent payment for that lot will be 95 percent. In areas where the grade exceeds the plan-grade tolerances by more than 50 percent, the Contracting Officer will require removal of the deficient area and replacement with fresh paving mixture. The Contracting Officer will inform the Contractor in writing of the results of grade-conformance tests within 5 working days after completion of placement of a particular lot.

Smoothness requirements are dependent on pavement layer and pavement function, as shown in Table 9. Straightedge [3.66-m (12-ft)] measurements will be made longitudinally and transversely on mats at equal distances along the joint not to exceed 8 m (25 ft). When more than 5 percent of all measurements made within a lot are outside the specified tolerances, the computed percent payment for that lot will be 95 percent. In areas where the grade exceeds the plan-grade tolerances by more than 50 percent, the Contracting Officer will require removal of the deficient area and replacement with fresh paving mixture. In addition, any pavement area having an abrupt offset of 3 mm or more, in the intermediate course or wearing course, in either the lane interior or at a joint, will be rejected and the affected area shall be removed and replaced as directed.

Summary

The acceptance characteristics for the specifications used by the three agencies included in this chapter are summarized in Table 10. Principal differences can be summarized as follows.

a. The FHWA and the FAA use Quality Index statistical concepts, while the USACE uses mean absolute deviation and simple averages.

b. The FHWA recommends sampling rates based on material production within lots, while the FAA and the USACE divide lots into four equal-size sublots and then sample randomly within sublots.

c. The FHWA and USACE include asphalt content and aggregate gradation in their acceptance testing, while the FAA uses laboratory-compacted mixture air voids.

d. The FHWA uses both profilograph measurements and straightedge measurements for smoothness, while the FAA and the USACE use only straightedge measurements.

e. Both the FHWA and the FAA use some of their acceptance testing as "flags" for evaluating production processes or for stopping production.

They do not implement all of their acceptance testing in payment adjustment schedules. The USACE uses all of its acceptance testing results in payment adjustment schedules.

Table 1
FHWA Pay Factors (after FHWA 1992)

Pay Factor Category I	Pay Factor Category II	Maximum Allowable Percent of Work Outside Specification Limits for a Given Pay Factor (P_U + P_L) n=5	n=6	n=7	n=8	n=9	n= 10, 11	n= 12, 14	n= 15, 17	n= 18, 22	n= 23, 29	n= 30, 42	n= 43, 66	n= 66+
1.05	[1]	[1]	[1]	[1]	0	0	0	0	0	0	0	0	0	0
1.04	[1]	[1]	[1]	0	1	3	5	4	4	4	3	3	3	3
1.03	[1]	[1]	0	2	4	6	8	7	7	6	5	5	4	4
1.02	[1]	[1]	1	3	6	9	11	10	9	8	7	7	6	6
1.01	[1]	0	2	5	8	11	13	12	11	10	9	8	8	7
1.00	[1]	22	20	18	17	16	15	14	13	12	11	10	9	8
0.99	[1]	24	22	20	19	18	17	16	15	14	13	11	10	9
0.98	[1]	26	24	22	21	20	19	18	16	15	14	13	12	10
0.97	[1]	28	26	24	23	22	21	19	18	17	16	14	13	12
0.96	[1]	30	28	26	25	24	22	21	19	18	17	16	14	13
0.95	1.00	32	29	28	26	25	24	22	21	20	18	17	16	14
0.94	0.99	33	31	29	28	27	25	24	22	21	20	18	17	15
0.93	0.98	35	33	31	29	28	27	25	24	22	21	20	18	16
0.92	0.97	37	34	32	31	30	28	27	25	24	22	21	19	18
0.91	0.96	38	36	34	32	31	30	28	26	25	24	22	21	19
0.90	0.95	39	37	35	34	33	31	29	28	26	25	23	22	20
0.89	0.94	41	38	37	35	34	32	31	29	28	26	25	23	21
0.88	0.93	42	40	38	36	35	34	32	30	29	27	26	24	22
0.87	0.92	43	41	39	38	37	35	33	32	30	29	27	25	23
0.86	0.91	45	42	41	39	38	36	34	33	31	30	28	26	24
0.85	0.90	46	44	42	40	39	38	36	34	33	31	29	28	25
0.84	0.89	47	45	43	42	40	39	37	35	34	32	30	29	27
0.83	0.88	49	46	44	43	42	40	38	36	35	33	31	30	28
0.82	0.87	50	47	46	44	43	41	39	38	36	34	33	31	29
0.81	0.86	51	49	47	45	44	42	41	39	37	36	34	32	30
0.80	0.85	52	50	48	46	45	44	42	40	38	37	35	33	31
0.79	0.84	54	51	49	48	46	45	43	41	39	38	36	34	32
0.78	0.83	55	52	50	49	48	46	44	42	41	39	37	35	33
0.77	0.82	56	54	52	50	49	47	45	43	42	40	38	36	34
0.76	0.81	57	55	53	51	50	48	46	44	43	41	39	37	35
0.75	0.80	58	56	54	52	51	49	47	46	44	42	40	38	36
RE-JECT	0.79	60	57	55	53	52	51	48	47	45	43	41	40	37
	0.78	61	58	56	55	53	52	50	48	46	44	43	41	38
	0.77	62	59	57	56	54	53	51	49	47	45	44	42	39
	0.76	63	61	58	57	55	54	52	50	48	47	45	43	40
	0.75	64	62	60	58	57	55	53	51	49	48	46	44	41
	RE-JECT	Value Greater Than Those Shown Above												

Note: To obtain a pay factor when the estimated percent outside specification limits does not correspond to a value in the table, use the next larger value.

[1] No entry.

Table 2 FHWA Aggregate Gradation Target Value Ranges and (Allowable Deviations) (after FHWA 1992)						
	Percent by Weight Passing					
	Grading Designation					
Sieve Size	A	B	C	D	E	F
50 mm (2 in.)	100	[1]	[1]	[1]	[1]	[1]
37.5 mm (1.5 in.)	97-100	100	[1]	[1]	[1]	[1]
25 mm (1 in.)	[1]	97-100	100	[1]	[1]	[1]
19 mm (3/4 in.)	66-80 (5)	[1]	97-100	100	[1]	[1]
12.5 mm (1/2 in.)	[1]	[1]	76-88 (5)	97-100	[1]	[1]
9.5 mm (3/8 in.)	48-60 (6)	53-70 (6)	[1]	[1]	100	100
4.75 mm (No. 4)	33-45 (5)	40-52 (6)	49-59 (7)	57-69 (6)	97-100	33-47 (6)
2.36 mm (No. 8)	25-33 (4)	25-39 (4)	36-45 (5)	41-49 (6)	62-81 (5)	7-13 (4)
600 μm (No. 30)	11-20 (4)	12-22 (4)	20-28 (4)	22-30 (4)	28-44 (4)	[1]
300 μm (No. 50)	7-15 (3)	8-16 (3)	13-21 (3)	13-21 (3)	18-31 (3)	[1]
75 μm (No. 200)	3-8 (2)	3-8 (2)	3-7 (2)	3-8 (2)	7-16 (2)	2-4 (2)

Note: Statistical acceptance procedures do not apply to sieves with 100 percent or 97 percent to 100 percent passing.
[1] No entry.

Table 3 Maximum Profile Index (after FHWA 1992)		
	Profile Index - mm/km (in./mi)	
Pavement Smoothness Type	Upper Specification Limit	Defective Limit
I	80 (5)	160 (10)
II	125 (8)	190 (12)
III	160 (10)	240 (15)

Table 4
Acceptance Limits (after FAA 1994)

Test Property	50 Marshall Hammer Blows per Face[1]		75 Marshall Hammer Blows per Face[2]	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit
Stability, min. N (lb)	4,450 (1,000)	[3]	8,010 (1,800)	[3]
Flow, 0.25 mm (0.01 in.)	8	20	8	16
Air Voids, %	2.0	5.0	2.0	5.0
Mat Density, %	96.3	[3]	96.3	[3]
Joint Density, %	93.3	[3]	93.3	[3]

[1] Pavements designed for aircraft gross weight less than (60,000 lb) or tire pressure less than (100 psi).
[2] Pavements designed for aircraft gross weight greater than or equal to (60,000 lb) or tire pressure greater than or equal to (100 psi).
[3] No entry.

Table 5
Price Adjustment Schedule (after FAA 1994)

Percentage of Material Within the Specification Limits (PWL)	Percent of Contract Unit Price to be Paid
90-100	100
80-90	0.5 (PWL) + 55
65-80	2.0 (PWL) - 65
Below 65	Reject[1]

[1] The lot shall be removed and replaced. However, the Engineer may decide to accept the deficient lot. In that case, if the Engineer and Contractor agree in writing that the lot shall not be removed, it will be paid for at 50 percent of the contract price.

Table 6
Percent Payment Based on Asphalt Cement Content (after USACE 1989 and USACE 1991)

50 Marshall Hammer Blows per Face (after USACE 1989)		75 Marshall Hammer Blows per Face (after USACE 1991)	
Mean Absolute Deviation[1]	**Percent Payment**	**Mean Absolute Deviation[1]**	**Percent Payment**
Less than 0.25	100	0.25 or less	100
0.26 to 0.30	98	0.26 to 0.35	98
0.31 to 0.35	95	0.36 to 0.40	95
0.36 to 0.40	90	0.41 to 0.45	90
Greater then 0.40	Reject	Greater than 0.45	Reject

[1] Deviation between extracted asphalt cement content and the job-mix formula.

Table 7
Percent Payment Based on Aggregate Gradation (after USACE 1989 and USACE 1991)

Sieve Size (mm)	Mean Absolute Deviation[1]						
	0.0 - 1.0	**1.1 - 2.0**	**2.1 - 3.0**	**3.1 - 4.0**	**4.1 - 5.0**	**5.1 - 6.0**	**> 6.0**
19.0	100	100	100	100	98	95	90
12.5	100	100	100	100	98	95	90
9.5	100	100	100	100	98	95	90
4.75	100	100	100	100	98	95	90
2.36	100	100	100	98	95	90	Reject
1.18	100	100	100	98	95	90	Reject
0.60	100	100	100	98	95	90	Reject
0.30	100	100	100	98	95	90	Reject
0.15	100	98	95	90	90	Reject	Reject
0.075	100	98	90	Reject	Reject	Reject	Reject

[1] Deviation between percent passing each sieve size for extracted aggregate and the job-mix formula.

Table 8
Percent Payment Based on Relative Density (after USACE 1989 and USACE 1991)

50 Marshall hammer blows per face (after USACE 1989)			75 Marshall hammer blows per face (after USACE 1991)		
Mat Density[1] (%)	Percent Payment	Joint Density[1] (%)	Mat Density[1] (%)	Percent Payment	Joint Density[1] (%)
97.0 to 100.0	100.0	≥95.0	98.0 to 100.0	100.0	≥96.5
96.9	100.0	94.9	97.9	100.0	96.4
96.8 or 100.1	99.9	94.8	97.8 or 100.1	99.9	96.3
96.7	99.8	94.7	97.7	99.8	96.2
96.6 or 100.2	99.6	94.6	97.6 or 100.2	99.6	96.1
96.5	99.4	94.5	97.5	99.4	96.0
96.4 or 100.3	99.1	94.4	97.4 or 100.3	99.1	95.9
96.3	98.7	94.3	97.3	98.7	95.8
96.2 or 100.4	98.3	94.2	97.2 or 100.4	98.3	95.7
96.1	97.8	94.1	97.1	97.8	95.6
96.0 or 100.5	97.3	94.0	97.0 or 100.5	97.3	95.5
95.9	96.3	93.9	96.9	96.3	95.4
95.8 or 100.6	94.1	93.8	96.8 or 100.6	94.1	95.3
95.7	92.2	93.7	96.7	92.2	95.2
95.6 or 100.7	90.3	93.6	96.6 or 100.7	90.3	95.1
95.5	87.9	93.5	96.5	87.9	95.0
95.4 or 100.8	85.7	93.4	96.4 or 100.8	85.7	94.9
95.3	83.3	93.3	96.3	83.3	94.8
95.2 or 100.9	80.6	93.2	96.2 or 100.9	80.6	94.7
95.1	78.0	93.1	96.1	78.0	94.6
95.0 or 101.0	75.0	93.0	96.0 or 101.0	75.0	94.5
<95.0 or >101.0	Reject	<93.0	<96.0 or >101.0	Reject	<94.5

[1] Average relative density (relative to laboratory compaction).

Table 9
Surface Smoothness Requirements[1] (after USACE 1989 and USACE 1991)

Pavement Category	Direction of Testing	Intermediate Course	Wearing Course
Runways and taxiways	Longitudinal	6	3
	Transverse	6	6
Hardstands and compass swinging bases	Longitudinal	6	5
	Transverse	6	5
All other airfield and helicopter paved areas	Longitudinal	6	6
	Transverse	6	6
Roadways	Longitudinal	---	6
	Transverse	---	6

[1] Maximum deviation from a 3.66-m (12-ft) straightedge, mm.

Table 10
Acceptance Characteristics of Specifications

Characteristic	FHWA	FAA	USACE
Statistical Method	Percent Defective (based on Quality Index)	Percent Within Limits (based on Quality Index)	Mean Absolute Deviation and Simple Average
Lot Size	Total project, unless changes in materials	≤ 1,814,000 kg (2,000 tons)	≤ 1,814,000 kg (2,000 tons)
Sampling Rate	Sampling rates established by state agencies	4 equal-size sublots per lot; one sample per sublot	4 equal-size sublots per lot; one sample per sublot
Acceptance Testing (* = included in pay adjustment calculations)[1]	Asphalt content* Aggregate gradation* Mat density* Profilometer* Straightedge	Air voids* Mat density* Stability Flow Joint density Thickness Straightedge Grade	Asphalt content* Aggregate gradation* Mat density* Joint density* Straightedge* Grade*
Range of Pay Factors	0.75 to 1.05	0.65 to 1.00	0.75 to 1.00

[1] Components of acceptance testing not included in pay adjustments are performed to determine the necessity of evaluating and/or stopping material production and/or correcting surface smoothness problems.

7 Statistical Acceptance Plan for the Corps of Engineers Pavement Specifications

The purpose of this chapter is to recommend modifications to the acceptance plan for U.S. Army Corps of Engineer guide specification for heavy-duty pavement construction, CEGS 02556, "Asphaltic Bituminous Heavy-Duty Pavement (Central-Plant Hot Mix)," (USACE 1991). Other elements of the specification that are known to have caused problems on job sites are also addressed. These recommended modifications are stated formally, in the form of an Engineering Technical Letter, included in Appendix D.

Due to the similarities between CEGS 02556 (USACE 1991) and the guide specification for light-duty pavements, CEGS 02551, "Bituminous Paving for Roads, Streets and Open Storage Areas," (USACE 1989), the recommendation provided in this chapter could be easily adapted for CEGS 02551 (USACE 1989).

The modifications to the acceptance plan will include a change from calculating mean absolute deviation to calculating fraction nonconforming. This change offers the following advantages:

a. Calculating fraction nonconforming facilitates other aspects of specification development. It permits a statistical approach to dividing risks associated with sampling between the buyer and the seller. It also facilitates a reasonable approach to assigning costs to the buyer that result from receiving a substandard product.

b. Standard deviation and mean among sublots, which are statistics required for the calculation of fraction nonconforming, provide the contractor with useful numbers for his process control. Monitoring mean absolute deviation, on the other hand, would not inform the contractor as to whether material variability is high or mean value has changed.

c. Acceptance plans involving the calculation of fraction nonconforming would be similar to the plans used by other agencies involved in pavement construction, namely the Federal Highway Administration (FHWA) and the Federal Aviation Administration (FAA). The advantage of implementing a plan similar in structure to these other agencies is related

to the enhancement of contractor familiarity. An asphalt paving contractor could be involved with either the FHWA, the FAA, or the Department of Defense (DOD) on any particular project. All agencies would benefit from any increases in the similarities between their specifications. A contractor is better able to bid on a project that involves a specification with which he/she is familiar. With improved familiarity, a contractor is also better able to fulfill his/her contractual obligations.

Historical Variability Data

In order to develop fair specifications for pavement characteristics, typical variabilities experienced in quality construction need to be established. A specification that requires the seller to provide a product with an unrealistically low variability would not be fair. Using a recently-published WES report (Freeman and Grogan 1997) and quality control/quality assurance data obtained on U.S. Army Corps of Engineers jobs as the primary sources of information, variabilities that can be expected for properties of interest for asphalt concrete are summarized in Table 11. Measures of variability shown include standard deviation and coefficient of variation. The standard deviations are shown as single values because they remained relatively constant with changes in the mean values of the material characteristics.

Acceptance Plan for Continuous Variables

The statistical acceptance plan considers each material characteristic as a continuous variable. Acceptance procedures require the calculation of fraction nonconforming (FN), using the quality index statistic, Q. The "fraction nonconforming" for a material characteristic represents the estimated fraction of a lot that falls outside of the specification limits. With this type of acceptance plan, the FN is calculated as follows.

$$FN = P(y < LL) + P(y > UL) = P(Q > Q_L) + P(Q > Q_U) \tag{84}$$

where

y = measured material characteristic

LL = lower limit

UL = upper limit

$$Q_L = \frac{\bar{y} - LL}{s} \tag{85}$$

$$Q_U = \frac{UL - \bar{y}}{s} \tag{86}$$

In order to determine $P(Q > Q_L)$ and $P(Q > Q_U)$, the calculated values for Q_L and Q_U are compared to standard quality index tables or the probabilities are calculated using the beta distribution, as shown in Appendix B. If FN $\leq$ c, the lot is accepted at full payment. If FN $>$ r, the lot is rejected. If c $<$ FN $\leq$ r, the lot is accepted at reduced payment.

Buyer and seller risks

Risks are a function of the following specification criteria: acceptable quality level (AQL), unacceptable quality level (UQL), rejection value (r), and acceptance value (c). Each of these criteria have units of fraction nonconforming. The AQL and UQL settings for material characteristics should reflect their relative importance in terms of pavement performance. In this statistical acceptance plan, asphalt cement content, fine aggregate grading (No. 8 sieve and smaller), mat density, and joint density all have AQL and UQL set at 0.05 and 0.30 fraction nonconforming, respectively. Coarse aggregate sieves (No. 4 sieve and larger) have AQL and UQL set at 0.10 and 0.40 fraction nonconforming, respectively. Coarse aggregate gradation is handled separately because it is viewed as having a lesser role in pavement performance, relative to asphalt cement content, fine aggregate grading, and field densities.

The *c* and *r* specification criteria must be set in a manner that ensures equitable party risks, relative to the established AQL and UQL. The risk calculations are independent of material variability, but they are dependent on sample size. Material variability does not need to be considered until the specification limits on material characteristics are to be set. The relationships between *c*, *r*, and party risks are dependent on sample size because the confidence in the judgements made from a sample increases as sample size increases.

The *c* and *r* values established for this statistical acceptance plan, along with the associated party risks, are shown in Tables 12 and 13. Table 12 is to be used for asphalt cement content, fine aggregate grading, mat density, and joint density. Table 13 is to be used for coarse aggregate grading. The primary risks shown in the tables are the same as those discussed in Chapter 5. The seller's primary risk, α_r, was referred to as α in Chapter 5. It represents the probability that a lot of material with quality AQL will be rejected. The buyer's primary risk, β_c, was referred to as β in Chapter 5. It represents the probability that a lot of material with quality UQL will be accepted at full payment. The secondary risks for the seller and buyer are designated α_c and β_r, respectively. The seller's secondary risk represents the probability that a lot of material with quality AQL will be either rejected or subjected to pay reduction. The buyer's secondary risk represents the probability that a lot of material with quality UQL will be either accepted at full price or accepted with a reduction in payment.

While establishing *c* and *r* for various sample sizes, the following rules for party risks were followed. Based on the review of literature, policies of other agencies, and judgement of the authors, these rules were believed to promote the development of equitable specifications.

a. The seller's primary risk should be approximately 5 percent or less.

b. The buyer's primary risk should be approximately 10 percent or less.

c. The buyer's secondary risk should be approximately 50 percent or less.

d. The seller's secondary risk should be less than the buyer's secondary risk.

A review of Tables 12 and 13 reveals that these rules were followed. The primary risks are smaller than the secondary risks because their associated errors are more costly. The risks for both parties decrease as the number of samples increases. Risks become easier to control as the confidence in sample statistics increases; confidence increases as the available information increases. Risk calculations were performed in a similar fashion as those shown in Chapter 5. They are included in Appendix C, along with operating characteristic curves.

Asphalt cement content

The upper and lower limits for asphalt cement content are set at the job-mix target ± 0.6 percent. The reasonableness of these limits, in relation to the AQL and UQL, can be demonstrated with the help of an assumed standard deviation for AC content. Using the data summarized in Table 11, a reasonable estimate for standard deviation for good quality construction is 0.20 percent. A normal distribution can be assumed in this analysis because field evaluations have shown that these distributions are typically normal in shape. If the population mean for AC content is equal to the target and the standard deviation is 0.20 percent, the true fraction of nonconforming material can be estimated with the standard normal statistic, Z. In this specification, the upper and lower limits are equidistant from the mean, so the Z statistics with respect to the upper and lower limits are equal.

$$z = \frac{UL - \mu}{\sigma} = \frac{\mu - LL}{\sigma} = \frac{0.6}{0.20} = 3.0 \qquad (87)$$

The probability of obtaining material outside the limits is equal to the probability of obtaining a standard normal value greater than 3.0. The absolute value in the following equation indicates a two-tail test.

$$P(Z > |3.0|) = 0.002 \qquad (88)$$

With a mean AC content equal to the target and with a standard deviation equal to 0.20 percent, the probability of obtaining an AC content outside the limits is 0.002. Since this probability is smaller than the established AQL (=0.05), these criteria would appear to be reasonable.

The UQL in this modified acceptance plan, along with the associated limits can also be tested for reasonableness with the help of the current version of

CEGS 02556 (USACE 1991). In this modified acceptance plan, an UQL was defined as a fraction nonconforming of greater than 0.30 when the conformance limits are set at target asphalt cement content ±0.6 percent. In the current version of CEGS 02556 (USACE 1991), a lot is rejected if the mean absolute deviation (MAD) for asphalt cement content is greater than 0.40. Three different cases of attaining a MAD of 0.40 will be presented and for each case the fraction nonconforming, according to the modified acceptance plan, will be calculated. In these hypothetical cases of attaining a MAD of 0.40, the distributions of AC contents are assumed to be either normal or uniform in shape. The assumption of normality has been shown to be realistic for most construction material measurements, including AC content. The uniform distribution provides a representation of the highest variability (largest entropy) that may be obtained for a univariate population.

Three different cases of attaining a MAD of 0.40 are as follows.

a. The mean AC content is equal to the target and the distribution is uniform. In order to achieve a MAD of 0.40, the range for the uniform distribution must extend from 0.8 percent below target to 0.8 percent above target. This uniform distribution is shown in Figure 15a.

b. The mean AC content is equal to either the target minus MAD=0.4 or the target plus MAD=0.4 and the distribution is uniform. In order to achieve a MAD of 0.40, the range for the uniform distribution must extend from the target to either target minus 0.8 percent or target plus 0.8 percent. This uniform distribution is shown in Figure 15b.

c. Similar to case No. 2, the mean AC content is equal to either the target minus MAD or the target plus MAD. In this case, however, the distribution is assumed to be normal with a standard deviation of 0.20 (selected from Table 15). This normal distribution is shown in Figure 16.

Figures 15 and 16 can be used to estimate the fraction of material that would fall outside of the limits used in the modified acceptance plan, which were defined previously as target AC content ±0.6 percent. Inspection of the figures reveals that for both cases No. 1 and No. 2, fraction nonconforming (FN) would equal to 0.25. The standard normal distribution can be used to estimate the fraction outside of limits for case No. 3.

$$Z = \frac{UL - MAD}{\sigma} = \frac{0.6 - 0.4}{0.20} = 1.0 \tag{89}$$

$$P(Z > 1.0) = 0.16 \tag{90}$$

In summary, the MAD limit specified in CEGS 02556 (USACE 1991) could correspond to a range of fractions of nonconforming material. Nonconforming material refers to that which falls outside of limits equal to the target AC content plus or minus 0.6 percent. Assumptions stated in this text resulted in a range of FN from 0.16 to 0.25. The use of an UQL of 0.30 for these AC

content limits in the modified acceptance plan would therefore appear to be reasonable.

Mat density

Mat density in this text refers to relative density, which is calculated as the ratio of mat density to laboratory compacted density, times 100 percent. The upper and lower limits for mat density are set at 102.0 percent and 95.0 percent, respectively. The reasonableness of these limits, in relation to the AQL and UQL, can be demonstrated with the help of an assumed standard deviation for mat density. Using the data summarized in Table 11, a reasonable estimate for standard deviation for good quality construction is 1.5 percent. A normal distribution can be assumed in this analysis because field evaluations have shown that these distributions are typically normal in shape.

If the population mean for mat density is in between the limits (at 98.5 percent) and the standard deviation is 1.5 percent, the true fraction of nonconforming material can be estimated with the standard normal statistic, Z. In this specification, the upper and lower limits are equidistant from the mean, so the Z statistics with respect to the upper and lower limits are equal.

$$z = \frac{UL - \mu}{\sigma} = \frac{\mu - LL}{\sigma} = \frac{3.5}{1.5} = 2.33 \tag{91}$$

The probability of obtaining material outside the limits is equal to the probability of obtaining a standard normal value greater than 2.33. The absolute value in the following equation indicates a two-tail test.

$$P(Z > |2.33|) = 0.02 \tag{92}$$

With a mean mat density equal to 98.0 percent and with a standard deviation equal to 1.5 percent, the probability of obtaining a density measurement outside the limits is 0.02. Since this probability is smaller than the established AQL (=0.05), these criteria would appear to be reasonable.

The UQL in this modified acceptance plan, along with the associated limits can be also be tested for reasonableness with the help of the current version of CEGS 02556 (USACE 1991). In this modified acceptance plan, an UQL was defined as a fraction nonconforming of greater than 0.30 when the conformance limits are set at 95.0 percent and 102.0 percent. In the current version of CEGS 02556 (USACE 1991), a lot is rejected if the mean mat density is less than 96.0 percent or greater than 101.0 percent. Two different cases of attaining rejectable material in the current specification will be presented and for each case the fraction nonconforming, according to the modified acceptance plan, will be calculated. In these hypothetical cases, the distributions of relative mat density are assumed to be normal.

Two different cases of attaining a rejectable material, according to the current specification, are as follows.

a. The mean mat density is equal to 96 percent and the distribution is normal with a standard deviation of 1.5 percent.

b. The mean mat density is equal to 101 percent and the distribution is normal with a standard deviation of 1.5 percent.

Figure 17 can be used to estimate the fraction of material that would fall outside of the limits used in the modified acceptance plan, which were defined previously as 95.0 to 102.0 relative density. The standard normal distribution can be used to estimate the fraction outside of limits. For case No. 1, we need only be concerned with the lower limit:

$$Z = \frac{\mu - LL}{\sigma} = \frac{96 - 95.0}{1.5} = 0.67 \tag{93}$$

$$P(Z > 0.67) = 0.25 \tag{94}$$

For case No. 2, we need only be concerned with the upper limit:

$$Z = \frac{UL - \mu}{\sigma} = \frac{102.0 - 101.0}{1.5} = 0.67 \tag{95}$$

$$P(Z > 0.67) = 0.25 \tag{96}$$

In summary, given a typical variability for relative mat density, the limits for mean mat density specified in CEGS 02556 (USACE 1991) correspond to fractions of nonconforming material of approxiamtely 0.25. Nonconforming material refers to that which falls outside of the recommended limits for the modified acceptance plan: 95.0 and 102.0 percent. The use of an UQL of 0.30 for these limits in the modified acceptance plan would therefore appear to be reasonable.

Joint density

Similar to mat density, joint density in this text refers to relative density, which is calculated as the ratio of joint density to laboratory compacted density, times 100 percent. A specification for joint density needs only a lower limit. If excessively high densities were a problem, they would be identified by the relative mat densities. The modified acceptance plan for joint density includes a lower limit of 93.5 percent. The reasonableness of this limit, in relation to the AQL and UQL, can be demonstrated with the help of an assumed standard deviation for joint density. The same standard deviation as that used for mat densities, 1.5 percent, will be used for joint densities. An evaluation of data at Waterways Experiment Station revealed that the variability of mat and joint densities is generally similar. A normal distribution can be assumed in this analysis because field evaluations have shown that these distributions are typically normal in shape.

If the population mean for mat density is in between the lower limit and 100 percent density (at 96.75 percent), the true fraction of nonconforming material can be estimated with the standard normal statistic, Z.

$$z = \frac{\mu - LL}{\sigma} = \frac{96.75 - 93.5}{1.5} = 2.17 \tag{97}$$

The probability of obtaining material outside the limits is equal to the probability of obtaining a standard normal value greater than 2.17. The absence of absolute value in the following equation indicates a one-tail test.

$$P(Z > 2.17) = 0.015 \tag{98}$$

With a mean mat density equal to 96.75 percent and with a standard deviation equal to 1.5 percent, the probability of obtaining a density measurement outside the limits is equal to 0.015. Since this probability is smaller than the established AQL (=0.05), these criteria would appear to be reasonable.

The UQL in this modified acceptance plan, along with the associated limits can also be tested for reasonableness with the help of the current version of CEGS 02556 (USACE 1991). In this modified acceptance plan, an UQL was defined as a fraction nonconforming of greater than 0.30 when the lower conformance limit is set at 93.5 percent. In the current version of CEGS 02556 (USACE 1991), a lot is rejected if the mean joint density is less than 94.5 percent. A single case of attaining rejectable material in the current specification will be presented and the fraction nonconforming, according to the modified acceptance plan, will be calculated. In this hypothetical case, the distribution of relative joint density is assumed to be normal.

The single case of attaining a rejectable material, according to the current specification, requires that the mean joint density is equal to 94.5 percent and the distribution is normal with a standard deviation of 1.5 percent.

Figure 18 can be used to estimate the fraction of material that would fall outside of the lower limit used in the modified acceptance plan, which was defined previously as 93.5 percent relative density. The standard normal distribution can be used to estimate the fraction outside of the limit.

$$Z = \frac{\mu - LL}{\sigma} = \frac{94.5 - 93.5}{1.5} = 0.67 \tag{99}$$

$$P(Z > 0.67) = 0.25 \tag{100}$$

In summary, given a typical variability for relative joint density, the limits for mean joint density specified in CEGS 02556 (USACE 1991) correspond to fractions of nonconforming material of approxiamtely 0.25. Nonconforming material refers to that which falls below the recommended lower limit for the modified acceptance plan: 94.0. The use of an UQL of 0.30 for these limits in the modified acceptance plan would therefore appear to be reasonable.

Aggregate grading

The upper and lower limits for each sieve were set at target ±3 times a standard deviation that should be reasonable for good-quality construction. The "reasonable" standard deviation for each sieve was selected from Table 11. Recall that designations for acceptable quality level (AQL) and unacceptable quality level (UQL) are dependent on sieve size; coarse aggregates and fine aggregates are treated differently. Fine aggregates are considered to include those particles passing the 4.76-mm (No. 4) sieve. Relative to coarse aggregates, changes in percent passing for fine aggregates typically have a more severe affect on pavement performance. This idea was incorporated into CEGS 02556 (USACE 1991) by not defining any rejection criteria for the coarse aggregate sieve sizes.

The selected AQL and the associated limits for all sieve sizes can be evaluated for reasonableness with the help of an assumed standard deviation for measurements of percent passing. A normal distribution can be assumed in this analysis because field evaluations have shown that these distributions are typically normal in shape. If the population mean for percent passing is at its job mix target value and the limits are at ±3 standard deviations, the true fraction of nonconforming material can be estimated with the standard normal statistic, Z.

$$z = \frac{UL-\mu}{\sigma} = \frac{\mu-LL}{\sigma} = \frac{3\sigma}{\sigma} = 3.0 \tag{101}$$

The probability of obtaining material outside the limits is equal to the probability of obtaining a standard normal value greater than 3.0. The absolute value in the following equation indicates a two-tail test.

$$P(Z > |3.0|) = 0.003 \tag{102}$$

With a mean percent fines equal to the job mix target and limits set at ±3 standard deviations, the probability of obtaining a measurement for percent passing outside the limits is equal to 0.003. Since this probability is smaller than both the established AQL for coarse aggregate (=0.10) and the established AQL for fine aggregate (=0.05), these criteria for acceptability would appear to be reasonable.

The UQL for fine aggregates in this modified acceptance plan, along with the associated limits, can be evaluated for reasonableness with the help of the current version of CEGS 02556 (USACE 1991). A similar evaluation can not be performed for coarse aggregates because the CEGS 02556 (USACE 1991) does not include rejection criteria for these sieve sizes. In the modified acceptance plan, an UQL for fine aggregates was defined as a fraction nonconforming of greater than 0.30 when the conformance limits are set at job mix target ±3 standard deviations. In the current version of CEGS 02556 (USACE 1991), the maximum permissible mean absolute deviation (MAD_{MAX}) is dependent on the sieve size. The following fine aggregate sieve sizes are assigned a MAD_{max} of 6.0 percent: 2.36 mm, 1.18 mm, 0.60 mm, and 0.30 mm. The

0.15 mm sieve is assigned a MAD_{max} of 5.0 percent. The 0.075 mm is assigned a MAD_{max} of 3.0 percent.

Three different cases of attaining the maximum permissible MAD are shown generically in Figures 19 and 20. Generic figures are needed because the maximum permissible MAD and the assumed reasonable standard deviations are not the same for all sieve sizes. The three different cases shown in Figure 18 can be described as follows.

a. The mean percent passing is equal to the target and the distribution of measurements is uniform. In order to achieve the MAD_{max}, the range for the uniform distribution must extend from target-2*(MAD_{max}) to target+2*(MAD_{max}). This uniform distribution is shown in Figure 19(a).

b. The mean percent passing is equal to either the target minus MAD_{max} or the target plus MAD_{max} and the distribution is uniform. In order to achieve a MAD_{max} of 3.0, the range for the uniform distribution must extend from the target to either target minus 6.0 percent or target plus 6.0 percent. This uniform distribution is shown in Figure 19(b).

c. Similar to case No. 2, the mean percent passing is equal to either the target minus MAD_{max} or the target plus MAD_{max}. In this case, however, the distribution is assumed to be normal with a standard deviation selected from Table 11. This normal distribution is shown in Figure 20.

Figures 19 and 20 can facilitate the estimation of the fraction of material that would fall outside of the limits used in the modified acceptance plan, which were defined previously as target percent fines ± 3 standard deviations. Inspection of Figure 19 reveals that cases No. 1 and No. 2 provide similar results for fraction nonconforming (FN).

$$FN = 1 - \frac{3\sigma}{2(MAD_{max})} \qquad (103)$$

Inspection of Figure 20 reveals that case No. 3 provides a standard normal z-value equal to the following.

$$Z = \frac{3\sigma - MAD_{max}}{\sigma} \qquad (104)$$

The fraction nonconforming can then be calculated as the probability of obtaining a z-value larger than that calculated. Calculated fractions of nonconforming material (FN) are summarized in Table 14 for cases No. 1 through 3. These are the FN that would be obtained under modified acceptance procedures for material that borders rejection according to the current CEGS 02556 (USACE 1991). The UQL of 0.30 established under modified procedures appears to be reasonable.

Grade and smoothness

Currently, the 02556 (USACE 1991) imposes similar acceptance plans for grade and smoothness. For grade, the specification states that "When more than 5 percent of all measurements made within a lot are outside the specified tolerances, the computed percent payment for that lot will be 95 percent. In areas where the grade exceeds the plan-grade tolerances given in paragraph Grade and Surface-Smoothness Requirements by more than 50 percent, the Contracting Officer will require removal of the deficient area and replacement with fresh paving mixture."

For smoothness, the specification states that "When more than 5 percent of all measurements along the joints or along the mat within a lot exceed the specified tolerance, the computed percent payment for that lot will be 95 percent. Any joint or mat area surface deviation which exceeds the surface-smoothness tolerances given in paragraph Grade and Surface-Smoothness Requirements by more than 50 percent shall be corrected to meet the specification requirements."

In practice, these measurements are rarely documented as part of acceptance procedures. Typically, the contractor monitors grade and smoothness as part of the quality control program. It is recommended that these measurements be considered in a manner that determines only whether a lot passes or requires correction. If the Contracting Officer feels that a particular lot has grade or smoothness problems, measurements can be obtained and corrections enforced if the problem in fact exists.

Since additional work is required, rather than a 5 percent decrease in payment, the criterion for failed measurements should be changed. In an effort to impose similar requirements as the Federal Aviation Administration specification (FAA 1994), this criterion could be changed to 15 percent. For grade, the first sentence could be rewritten, "When more than 15 percent of all measurements made within a lot are outside the specified tolerances, the Contractor must remove deficient areas and replace with new material. Deficient areas and method of rectification will be established by the Contracting Officer." The second sentence could remain unchanged.

For smoothness, the first sentence could be rewritten, "When more than 15 percent of all measurements along the joints or along the mat within a lot exceed the specified tolerance, the Contractor must either remove and replace deficient areas or correct these areas so that they meet the specification requirements. Deficient areas and method of rectification will be established by the Contracting Officer." The second sentence could remain unchanged.

Pay adjustments

Each of the acceptance plans, including those for continuous variables and attributes, have regions between acceptance at full pay and rejection that require pay adjustments. Recommended pay adjustments will be presented in

this section, followed by an explanation of the reasoning that went into their development.

Recall that the acceptance procedure for each continuous variable requires the calculation of fraction nonconforming, FN.

$$FN = P(y < LL) + P(y > UL) = P(Q > Q_L) + P(Q > Q_U) \tag{105}$$

where

y = continuous measurement for material quality,

$$Q_L = \frac{\bar{y} - LL}{s} \tag{106}$$

$$Q_U = \frac{UL - \bar{y}}{s} \tag{107}$$

In order to determine $P(Q > Q_L)$ and $P(Q > Q_U)$, the calculated values for Q_L and Q_U are compared to standard quality index tables or the probabilities are calculated using beta distributions, as shown in Appendix B.

Previously, the specification criteria for FN were presented for the continuous variables. Pay factors were mentioned as the manner by which marginal cases would be handled. A marginal case occurs when FN is between the acceptance criterion, c, and the rejection criterion, r. The following equation is recommended for calculating pay factors for all cases of continuous variables. The use of a continuous equation, rather than discrete steps for pay factors eliminates the potential for disputes when FN is on the borderline between steps. The equation assumes a simple linear change in pay factor between c and r.

$$PF = (1 - r) + \frac{r(r - FN)}{r - c} \tag{108}$$

Final payment is then calculated by multiplying PF by the bid price; the bid price may be a lump sum or a unit price.

$$Final\ Payment = PF \times bid\ price \tag{109}$$

The reasoning behind the development of the equation is simple and involves the following two assumptions.

a. If the fraction nonconforming is equal to the acceptance criterion, c, the pavement life is not substantially affected.

b. If the fraction nonconforming is equal to the rejection criterion, r, the fraction of pavement life lost because of the poor quality product is at least equal to r.

Recall from Tables 12 and 13 that as the number of sublots (sample size) increases, r decreases and the difference between r and c decreases. These values are reproduced in Tables 15 and 16. According to the pay factor equation, a decrease in both r and the difference between r and c causes the range of possible pay factors to decrease. This trend is reasonable because as the number of sublots (samples) available for testing increases, the confidence in the calculated mean and standard deviation increase, alleviating the need for pay factors. When few sublots are available, lots must be accepted with a lower estimated quality (higher FN) in order to keep seller risks reasonable. Although lots with a relatively high FN must be accepted, the pay should reflect the best estimate for quality. The relationships between pay factors, fraction nonconforming, and sample size are best shown with "expected payment curves." Expected payment curves, corresponding to Tables 12 and 13, are displayed in Figures 21 and 22, respectively.

The first assumption concerning equation development was established to reflect the fact that the seller will receive 100 percent payment as long as the FN is less than or equal to c. Depending on the number of sublots (sample size), this condition permits 100 percent payment for FN values as high as 0.15 for most materials and a value as high as 0.25 for coarse aggregates. The second assumption concerning equation development was established to serve as a starting point for justifying the magnitude of maximum pay factor.

Appropriate pay factors can be determined using a life-cycle cost analysis. They should be based on the present-worth cost of rescheduling future pavement rehabilitation due to loss of service life. The following equation for calculating pay factors was derived from basic engineering economics formulas (Weed 1982a). It has been shown to produce reasonable pay factors provided the input values are reasonably accurate (Aurilio and Raymond 1995). The equation takes into account the original cost of hot mix and allows for two resurfacings within the life span of the pavement.

$$PF = \frac{M_c + (R^{DL} - R^{EL}) \times \left(R_1 + \dfrac{R_2 R^{EO}}{1 - R^{EO}} \right)}{M_c} \tag{110}$$

where

M_c = cost of hot mix (\$/ton)

R = (1 + inflation rate)/(1 + interest rate)

DL = design life (years)

EL = expected life considering construction deficiency (years)

EO = expected life of overlays (years)

R_1 = cost of first resurfacing (\$/ton)

R_2 = cost of second resurfacing (\$/ton)

Recall that the development of the pay factor equation shown in Table 15 assumed that when FN=r the fraction of pavement life lost is at least equal to r. The equation developed by Weed (1982a), shown above, can therefore be used to evaluate the reasonableness of assigning PF=r when FN=r. A hypothetical situation, demonstrating Weed's equation follows. Suppose the initial cost of asphalt concrete materials is \$30/ton and that the total cost of resurfacing would be approximately \$50/ton. Suppose further that the design life of the pavement is 10 years and that the anticipated life for each overlay is 10 years. If the interest and inflation rates can be approximated as 7 percent and 3 percent, respectively, pay factor can be calculated as follows.

$$PF = \frac{30 + (0.963^{10} - 0.963^{EL}) \times \left(50 + \frac{(50) \cdot 0.963^{10}}{1 - 0.963^{10}}\right)}{30} \tag{111}$$

We can calculate pay factors for fractions of lost pavement life equal to 0.10, 0.20 and 0.30. Relative to the pavement design life, these fractions of lost life correspond to expected lives of 9 years, 8 years, and 7 years. The results are summarized in Table 17. According to Weed's equation, the appropriate pay factors for these cases is approximately

$$PF = 1 - 2.5 \times (\textit{fraction of lost pavement life}) \tag{112}$$

Therefore, the pay factor equation recommended for CEGS 02556, which is equal to the fraction of lost pavement life, would appear to be relatively lenient for the seller.

Of course, this analysis does nothing to justify that having FN=r results in a fraction loss of pavement life equal to FN. At this point in time, this statement is based on engineering judgment.

Overall pay adjustment

Since several material characteristics can affect payment, the specification needs to explain the method by which the overall pay adjustment will be calculated. The current guide specification, CEGS 02556 (USACE 1991), states that, "The lowest computed percent payment determined for any pavement characteristic (i.e., gradation, asphalt content, density, grade, and smoothness) discussed below shall be the actual percent payment for that lot. The actual percent payment is applied to the bid price and the quantity of bituminous mixture placed in the lot to determined actual payment."

Prior to comparing percent payments for all material characteristics, the CEGS 02556 (USACE 1991) requires an adjustment for the percent payment for joint density if the acceptability of joint density is other than either 100 percent payment or rejection. The percent payment for joint density is adjusted to account for the length of longitudinal joints, relative to the overall size of the lot placement. Essentially, the severity of any pay reduction is reduced as the ratio of joint length to mat area decreases. This adjustment is equitable and is

incorporated into the proposed Engineering Technical Letter, shown in Appendix D.

The concept of using the lowest computed percent payment, among all material characteristics, is justifiable. The performance of a pavement is largely affected by its lowest-quality characteristic; high-quality characteristics do not compensate for deficient characteristics. For example, asphalt concrete with a low asphalt cement content may have a reduced life as a result of durability problems. The potential for costly repairs in the future is not decreased if the gradation happens to be perfect. If the low asphalt cement content also happens to cause density problems, the contractor will not be subjected to any form of double penalty because only the lowest pay factor is enforced; there is no cumulative penalty. Therefore, the only changes needed for the first sentence quoted earlier are related to the list of material measurements and to the incorporation of the term "pay factor." The sentence can now state that, "The lowest computed pay factor determined for any pavement characteristic (i.e., asphalt content, mat density, joint density, and aggregate gradation) discussed below shall be the final pay factor for that lot."

The second sentence quoted from CEGS 02556 (USACE 1991) requires changes to avoid ambiguity and to incorporate the term "pay factor." Currently, the sentence could be construed as stating that the percent payment is applied to both the bid price and the quantity of material, which would be a double penalty. This sentence can now state that, "The final pay factor is applied to the bid price, which could be in the form of either a lump-sum or a unit price."

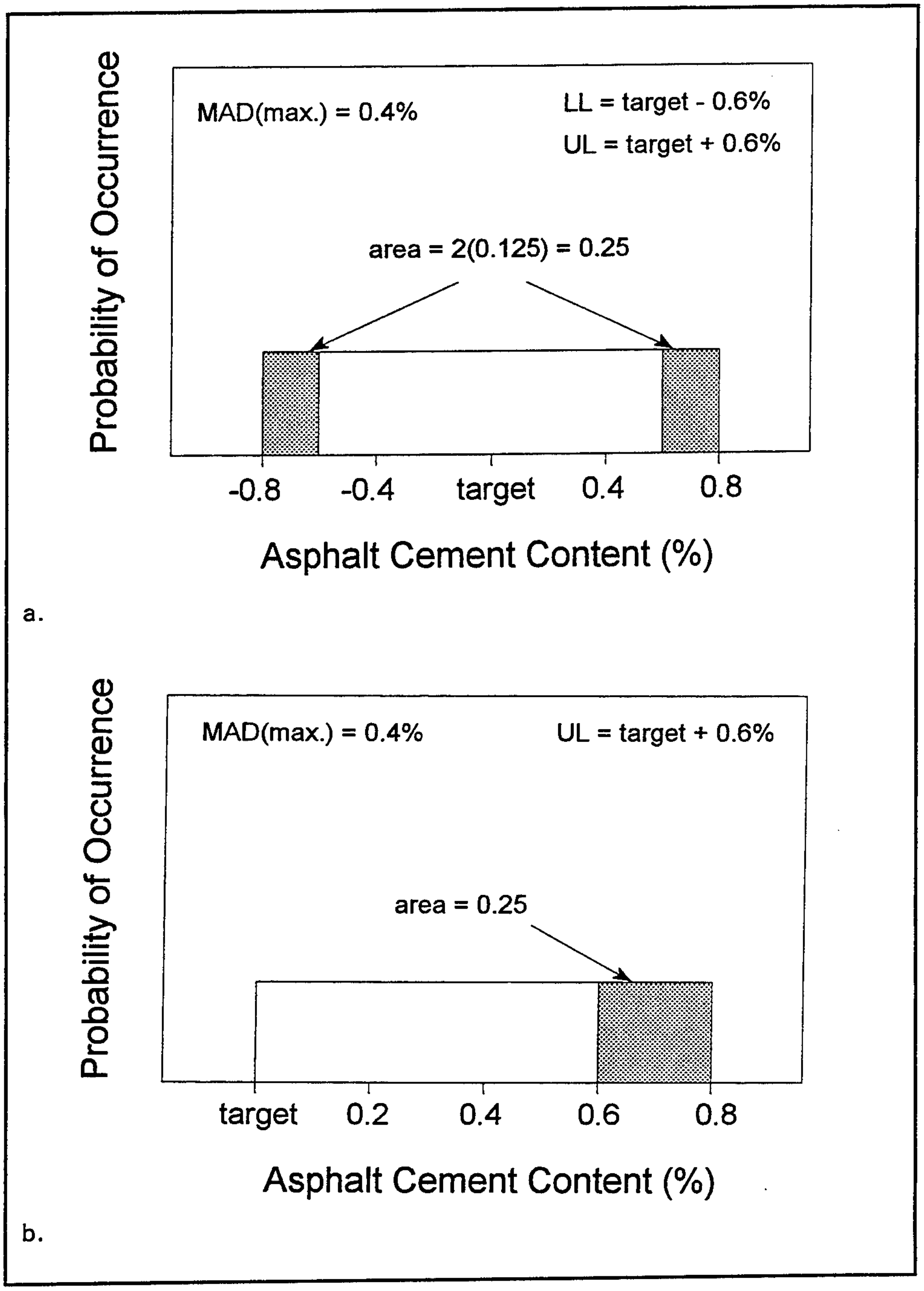

Figure 15. Hypothetical uniform distributions meeting the CEGS 02556 rejection criterion for asphalt cement content

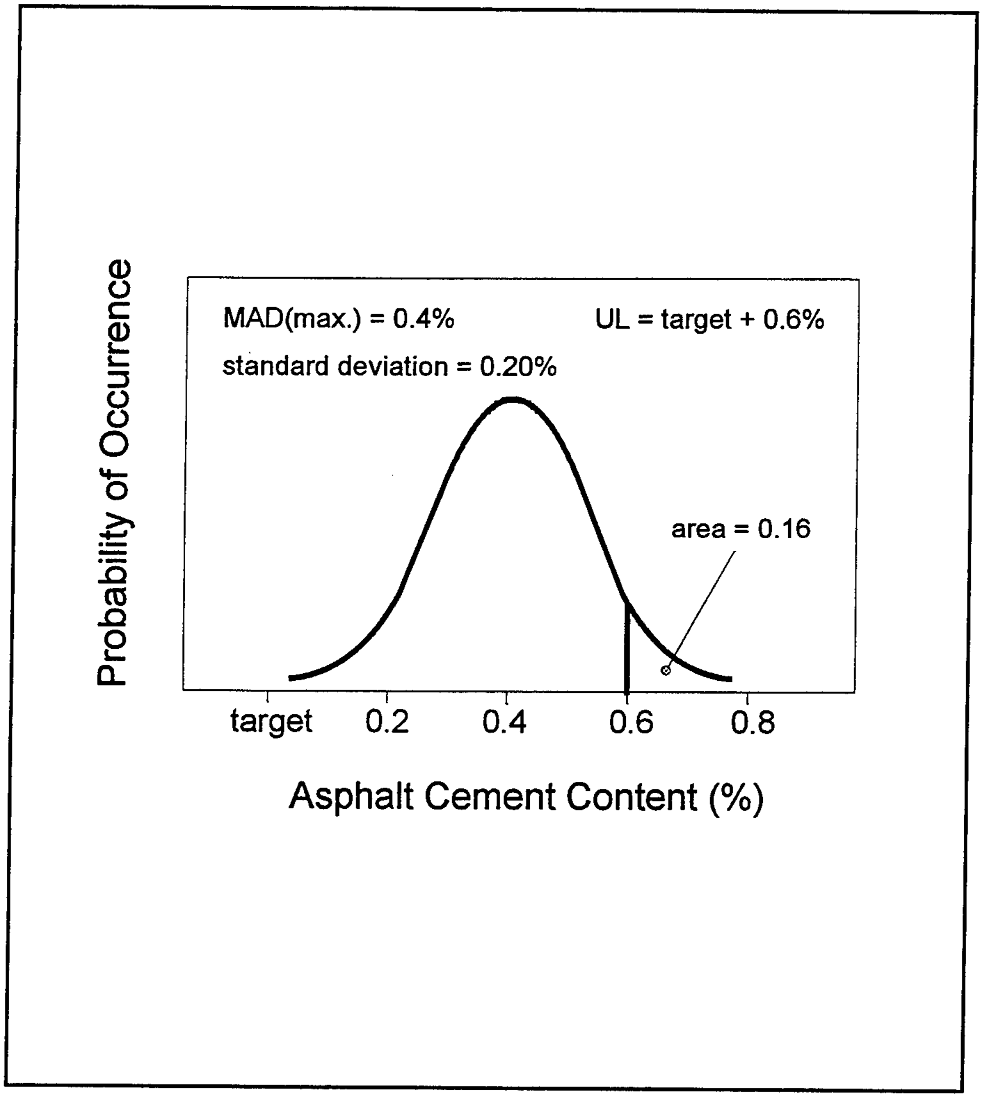

Figure 16. Hypothetical normal distribution meeting the CEGS 02556 rejection criterion for asphalt cement content

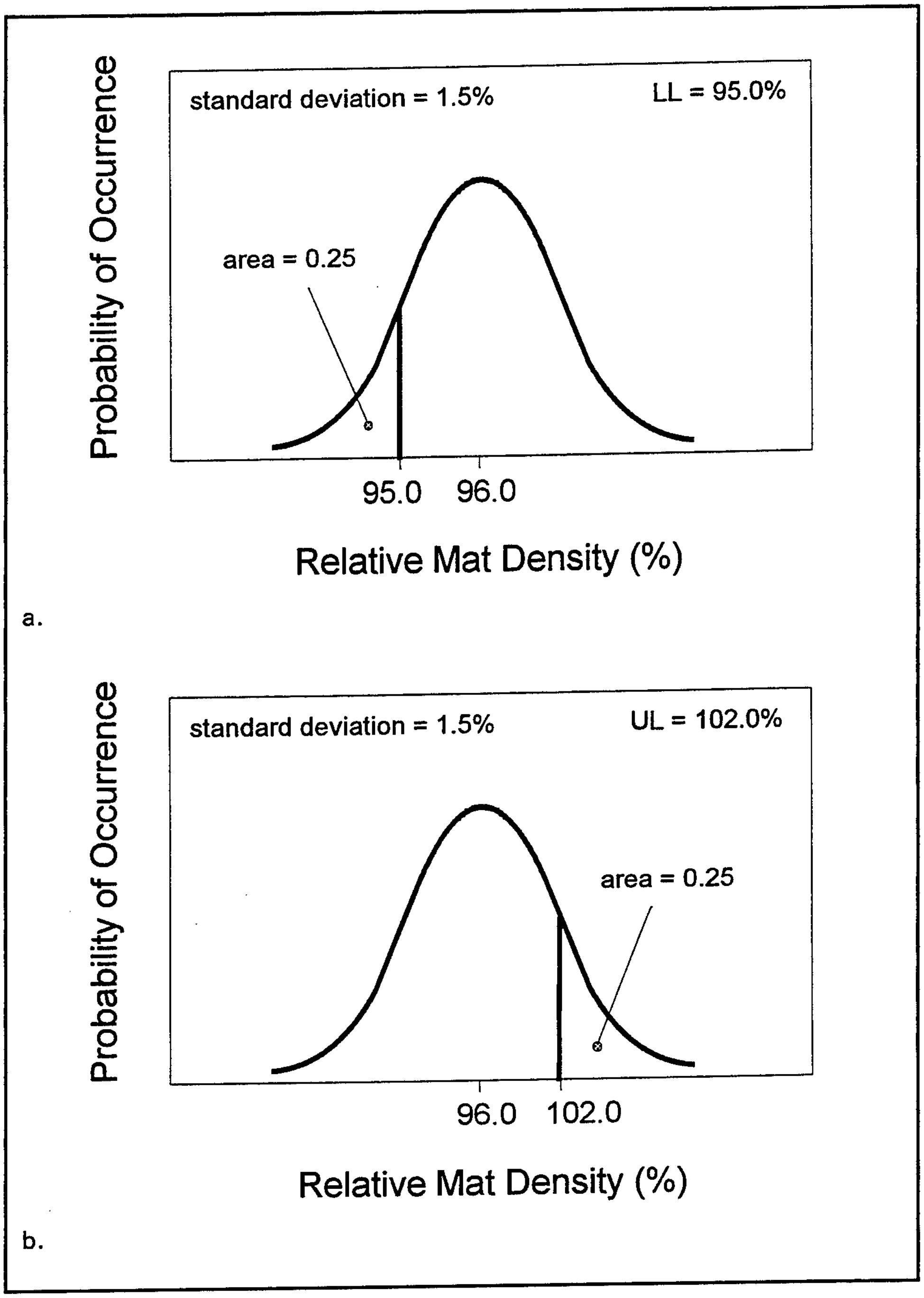

Figure 17. Hypothetical normal distributions meeting the CEGS 02556 rejection criterion for relative mat density

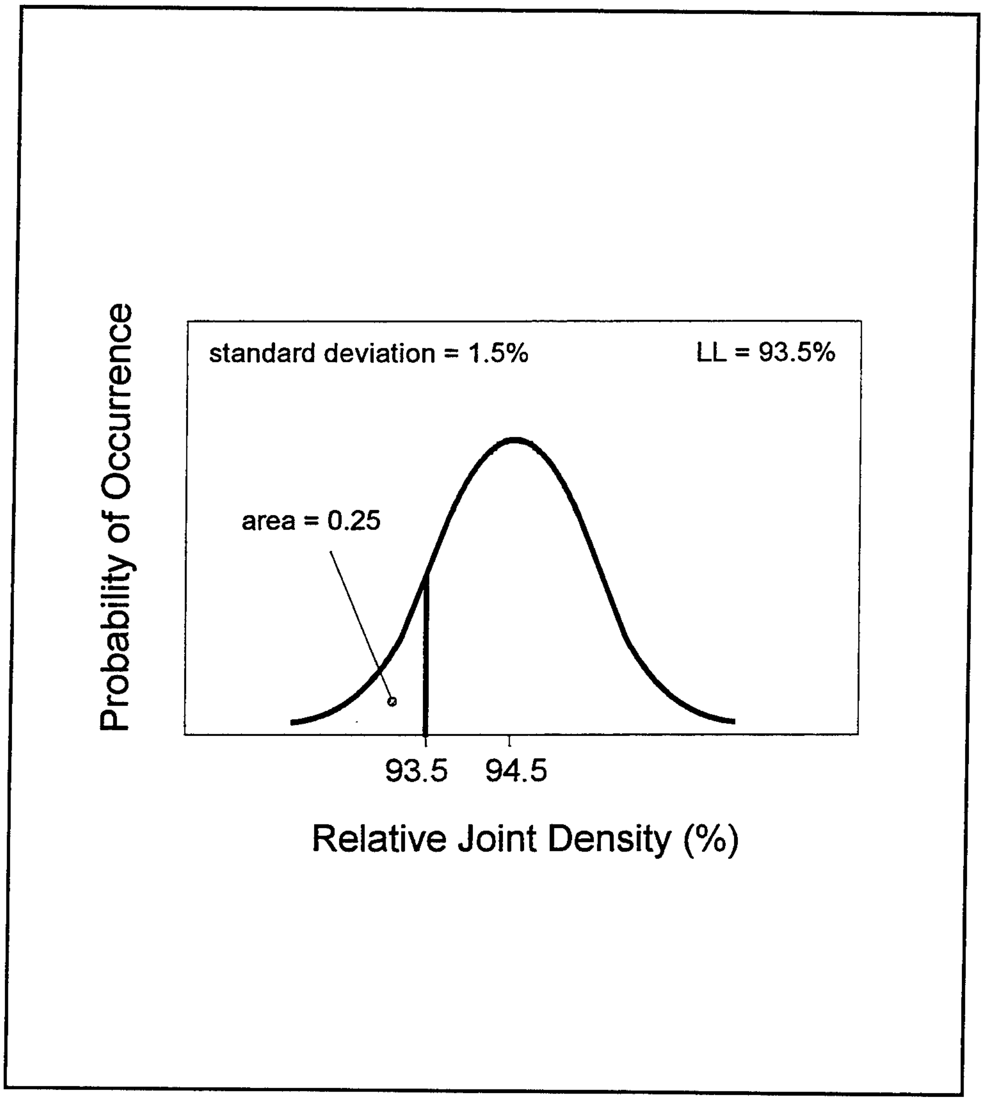

Figure 18. Hypothetical normal distribution meeting the CEGS 02556 rejection criterion for relative joint density

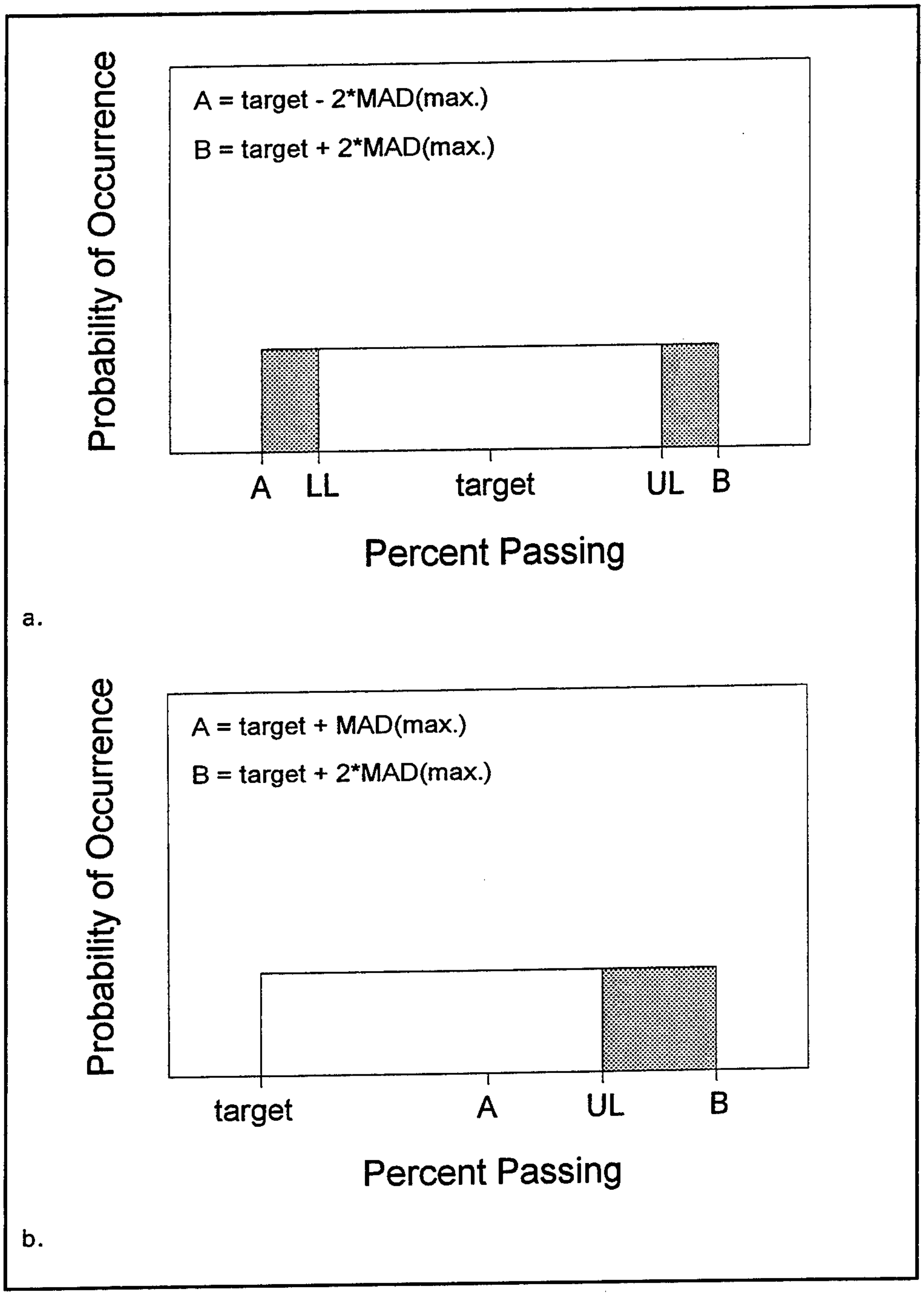

Figure 19. Hypothetical uniform distributions meeting the CEGS 02556 rejection criterion for fine aggregate grading

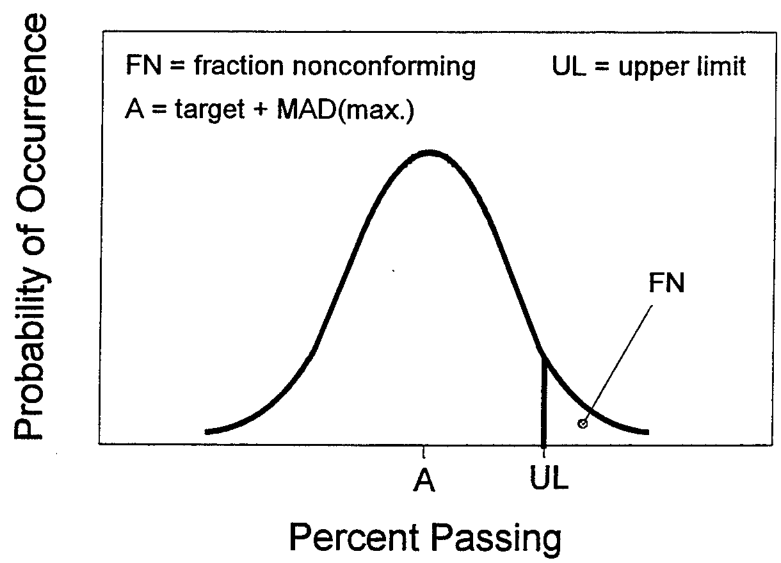

Figure 20. Hypothetical normal distribution meeting the CEGS 02556 rejection criterion for fine aggregate grading

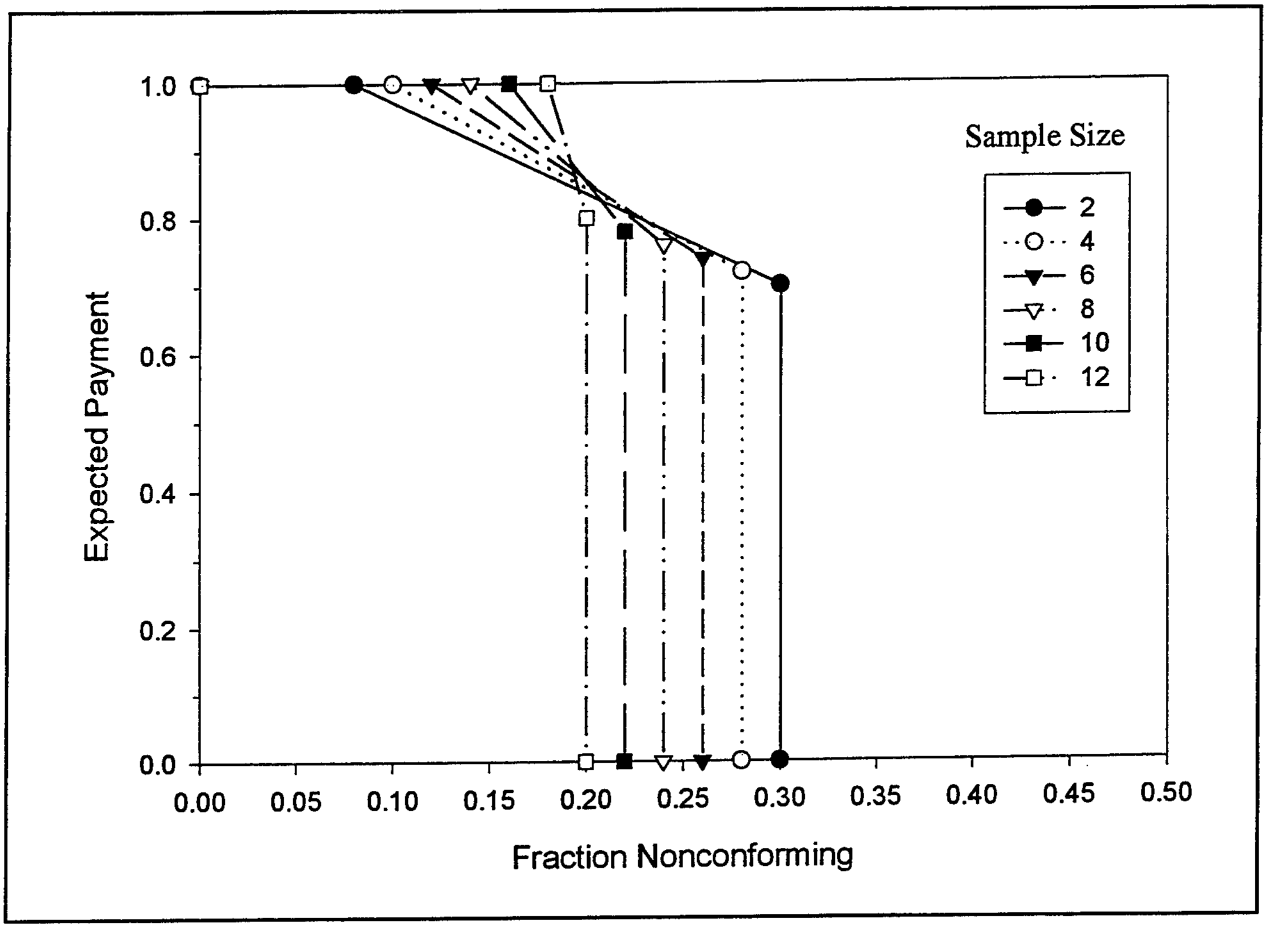

Figure 21. Pay factor plot for asphalt cement content, fine aggregate grading, and field density

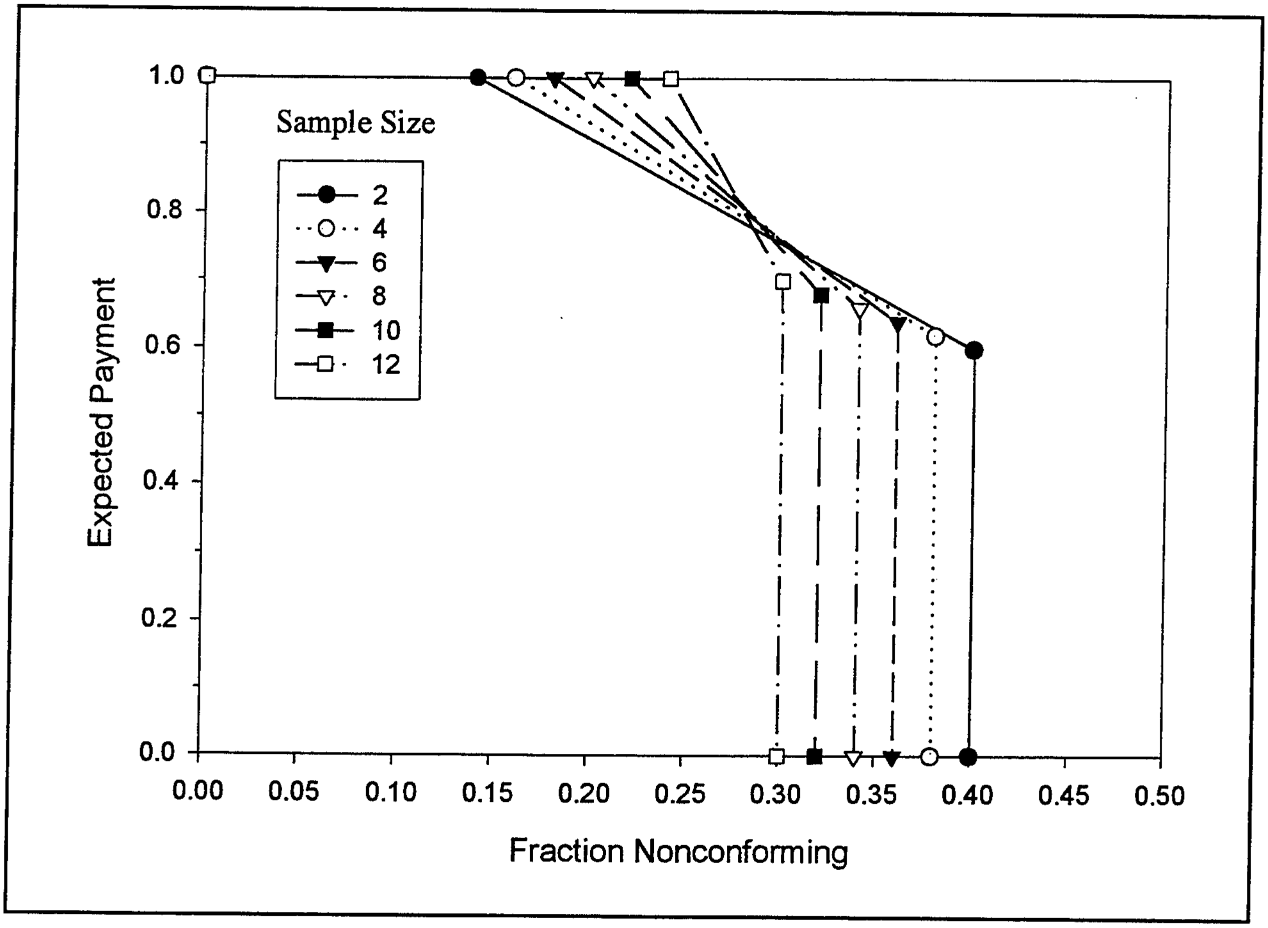

Figure 22. Pay factor plot for coarse aggregate grading

Table 11
Typical Variabilities for Selected Asphalt Concrete Properties

Property	Units for Standard Deviation	Standard Deviation	Coefficient of Variation (%)
Asphalt Cement Content	Percent by total mass	0.20	< 10
Aggregate Gradation	Particles finer by mass		
- 19-mm (3/4-in.) sieve		2.0	< 5
- 12.5-mm (1/2-in.) sieve		2.5	< 5
- 9.5-mm (3/8-in.) sieve		3.0	< 5
- 4.75-mm (No. 4) sieve		3.0	< 10
- 2.36-mm (No. 8) sieve		3.0	< 10
- 1.18-mm (No. 16) sieve		3.0	< 10
- 0.60-mm (No. 30) sieve		3.0	< 10
- 0.30-mm (No. 50) sieve		2.5	< 10
- 0.15-mm (No. 100) sieve		2.0	< 10
- 0.075-mm (No. 200) sieve		1.5	< 20
Mat and Joint Density	Percent relative to the density of laboratory-compacted specimens	1.5	< 5
Mat Thickness	mm	8.0	< 10
Marshall Stability	Kn	1.5	< 15
Marshall Flow	0.25-mm	1.0	< 15
Voids Total Mix	Percent by total volume	1.0	< 65
Voids Filled	Percent by total volume	5.0	< 10

Table 12
Acceptance Criteria for Asphalt Cement Content, Mat Density, Joint Density, and Fine Aggregates (No. 8 Sieve Through No. 200 Sieve)

Number of Samples (n)	Acceptance Value for FN, c	Rejection Value for FN, r	Primary Risks		Secondary Risks	
			Seller's Risk, α_r	Buyer's Risk, β_c	Seller's Risk, α_c	Buyer's Risk, β_r
2	0.08	0.30	0.057	0.107	0.367	0.500
3	0.09	0.29	0.029	0.079	0.299	0.480
4	0.10	0.28	0.017	0.065	0.234	0.454
5	0.11	0.27	0.011	0.058	0.175	0.422
6	0.12	0.26	0.007	0.056	0.125	0.385
7	0.13	0.25	0.005	0.056	0.085	0.346
8	0.14	0.24	0.004	0.058	0.055	0.304
9	0.15	0.23	0.003	0.062	0.034	0.260
10	0.16	0.22	0.003	0.069	0.020	0.217
11	0.17	0.21	0.003	0.077	0.011	0.175
12	0.18	0.20	0.003	0.088	0.006	0.136

Table 13
Acceptance Criteria for Coarse Aggregates (19.0 mm Through No. 4 Sieve)

Number of Samples (n)	Acceptance Value for FN, c	Rejection Value for FN, r	Primary Risks		Secondary Risks	
			Seller's Risk, α_r	Buyer's Risk, β_c	Seller's Risk, α_c	Buyer's Risk, β_r
2	0.14	0.40	0.073	0.121	0.388	0.500
3	0.15	0.39	0.041	0.088	0.336	0.482
4	0.16	0.38	0.026	0.069	0.283	0.459
5	0.17	0.37	0.017	0.059	0.232	0.430
6	0.18	0.36	0.012	0.052	0.185	0.398
7	0.19	0.35	0.009	0.049	0.143	0.364
8	0.20	0.34	0.007	0.048	0.107	0.326
9	0.21	0.33	0.006	0.049	0.077	0.288
10	0.22	0.32	0.005	0.050	0.054	0.249
11	0.23	0.31	0.005	0.054	0.036	0.211
12	0.24	0.30	0.004	0.058	0.023	0.174

Table 14
Summary of Data Evaluating the Reasonableness of UQL = 0.30 for Fine Aggregates

Sieve Size	Standard Deviation	MAD_{max}	FN for Cases No. 1 and 2	FN for Case No. 3
2.36-mm (No. 8)	3.0	6.0	0.25	0.16
1.18-mm (No. 16)	3.0	6.0	0.25	0.16
0.60-mm (No. 30)	3.0	6.0	0.25	0.16
0.30-mm (No. 50)	2.5	6.0	0.38	0.27
0.15-mm (No. 100)	2.0	5.0	0.40	0.31
0.075-mm (No. 200)	1.5	3.0	0.25	0.16

Table 15
Pay Adjustments for Asphalt Cement Content, Mat Density, Joint Density, and Fine Aggregate Grading

Number of Sublots (n)	Acceptance Value for FN, c	Rejection Value for FN, r	Pay Adjustment Calculation[1] ($c < FN \leq r$)	Range of Pay Factors
2	0.08	0.30	$PF = (1-r) + r(r-FN)/(r-c)$	0.70 - 1.0
3	0.09	0.29		0.71 - 1.0
4	0.10	0.28		0.72 - 1.0
5	0.11	0.27		0.73 - 1.0
6	0.12	0.26		0.74 - 1.0
7	0.13	0.25		0.75 - 1.0
8	0.14	0.24		0.76 - 1.0
9	0.15	0.23		0.77 - 1.0
10	0.16	0.22		0.78 - 1.0
11	0.17	0.21		0.79 - 1.0
12	0.18	0.20		0.80 - 1.0

[1] PF=pay factor; final payment = PF*bid price.

Table 16
Pay Adjustments for Coarse Aggregates (19.0 mm Through No. 4 Sieve)

Number of Sublots (n)	Acceptance Value for FN, c	Rejection Value for FN, r	Pay Adjustment Calculation[1] ($c < FN \leq r$)	Range of Pay Factors
2	0.14	0.40	$PF = (1-r) + r(r-FN)/(r-c)$	0.60 - 1.0
3	0.15	0.39		0.61 - 1.0
4	0.16	0.38		0.62 - 1.0
5	0.17	0.37		0.63 - 1.0
6	0.18	0.36		0.64 - 1.0
7	0.19	0.35		0.65 - 1.0
8	0.20	0.34		0.66 - 1.0
9	0.21	0.33		0.67 - 1.0
10	0.22	0.32		0.68 - 1.0
11	0.23	0.31		0.69 - 1.0
12	0.24	0.30		0.70 - 1.0

[1]

Table 17
Calculated Pay Factor Based on Fraction of Lost Pavement Life

Fraction of Lost Pavement Life	Resulting Expected Pavement Life	Pay Factor
0.10	9	0.76
0.20	8	0.50
0.30	7	0.24

Note: Pavement design life = 10 years.

8 Evaluation of the Statistical Acceptance Plan

In this chapter, the recommended modifications to the guide specification for heavy-duty hot-mix asphalt pavements, CEGS 02556 (USACE 1991), are evaluated with the help of job-site data. The data were collected during an airfield paving project that will remain nameless to protect the interests of parties involved. The quality of the construction during this project can be considered relatively low. Therefore, this project serves its purpose conservatively; it can be used to ensure that the recommended modifications to the guide specification will allow for the detection of poor quality materials. The data collected during this project will not, however, be used to verify the reasonableness of the assumed material variabilities used during specification development. Considering the poor quality of the work, the variabilities for material characteristics should be higher than that normally encountered.

The job-mix formula for paving project is shown in Table 18, along with mixture design limits. The asphalt concrete was designed for high tire pressure traffic using 19.0-mm maximum size aggregate and the 75-blow Marshall procedure. This project included 38 lots of material. This number of lots occurred as a result of striving for four sublots per lot, as the current specification directs. The current acceptance plan for CEGS 02556 (USACE 1991) will be applied to the project data. Then the statistical acceptance plan will be applied to the same data, using the same lot structure. Finally, the statistical acceptance plan will be applied to the project data in a manner that will permit flexibility in the number of sublots per lot. This was mentioned previously as an advantage of the modified plan due to the potential for construction interruption.

The dates and times that samples were obtained from trucks are shown in Table 19. Lots consisted of four sublots in almost all cases. Time proceeds from left to right in each table row and lot numbers are chronological. The shading of table cells is intended to emphasize which samples were obtained from the same continuous paving process. Adjacent cells that are either both shaded or both non-shaded represent samples that were obtained without an intervening shut-down in the paving operations. Shading obviously does not match well with the lot structure. In order to force four sublots per lot, a single lot may include samples from two or three different continuous paving operations, which were separated by complete shut-down. This practice is not consistent with typical definitions for "lot," such as that provided by AASHTO R 10-92 (AASHTO 1995), "An isolated quantity of material from a single source; a measured

amount of construction assumed to be produced by the same process." Sample plans should be structured so that each lot is as uniform as possible.

Inspection of the shaded versus non-shaded cells in Table 19 reveals that each single continuous paving process included anywhere from 1 sample to 6 samples. Inspection of the table reveals that mixing samples from different continuous paving processes was not the only method used to force 4 sublots per lot. In lot 3, a fourth sample was needed for gradation and asphalt cement content analyses. Therefore, the field core was used as the source of material for extraction and subsequent sieving operations. In lots 18 and 26, asphalt content and gradation data, obtained for other lots, were reused. Finally, lots 33 and 38 were not forced to include 4 sublots; these lots were evaluated with only 3 sublots. The specification criteria were applied to these lots without adjustment, even though the criteria were developed for lots containing four sublots.

Results for acceptance testing, calculated with the lot structure just described, are summarized in Table 20 and are presented in more detail in Appendix E. Using the current criteria for CEGS 02556 (USACE 1991), 0 lots received full payment, 8 lots were rejected, and 30 lots were accepted at reduced payment. Using the statistical specification criteria, 17 lots received full pavement, 9 lots were rejected, and 12 lots were accepted at reduced payment. Although the modified specification may appear to be substantially more lenient, the overall pay adjustment for this project was calculated to be 70.5 percent and 72.8 percent for the current criteria and the modified criteria, respectively. These overall adjustments were calculated as an average pay adjustment, weighted for the number of sublots per lot. These calculations assumed that each sublot sample represented the same quantity of material and they could not adjust joint density pay reductions for the ratio of joint length to mat area. However, the errors imposed by these inaccuracies are expected to be negligible.

The overall pay adjustments are similar between plans, despite the large difference in the number of lots accepted at full price, because the distribution of pay adjustments is different for the two plans. The median pay adjustment under the current CEGS 02556 (USACE 1991) criteria is 91.3 percent and the median pay adjustment under the modified criteria is 87.5 percent. Under the current criteria, many of the lot pay adjustments were 95 or 98 percent. The execution of many small pay adjustments can be disconcerting to a contractor. The contractor may feel that the buyer can not possibly be pleased. The statistical specification accepted 17 lots (or 45 percent of the lots) at full payment, so the contractor could be confident that the buyer's expectations are realistic.

Table 20 also provides a comparison between the acceptance plans in terms of the material characteristics that caused penalization. For both plans, mat density caused the most lots to be rejected. For both plans, 3 lots were rejected due to problems related to either asphalt cement content or joint density. For both plans, 3 or fewer lots were rejected due to aggregate grading problems. However, relative to the statistical acceptance plan, the current guide specification acceptance plan imposed many more small pay adjustments due to aggregate grading.

The data for the paving project were analyzed a second time in order to take advantage of the flexibility of the modified acceptance procedure, in terms of the number of sublot samples per lot. The division of material into lots was based on grouping samples obtained during the same continuous paving operation, as shown in Table 21. The flexibility of the modified acceptance procedure is limited to two or more samples, so the two cases where continuous production provided only one sample had to be eliminated from the analysis. These two samples were obtained on 15 August 1997 and on 9 September 1997. The remaining samples produced 39 lots, with sizes ranging from 2 to 6 sublot samples, as shown in Figure 23. The most common number of sublots per lot was four. The tendency for a lot to include fewer than four sublots was stronger than the tendency for a lot to include more than four sublots.

Results for acceptance testing, calculated with the statistical acceptance plan and the revised lot structure, are summarized in Table 22. The results obtained with the statistical acceptance plan and the original lot structure are also included in Table 8-5. The results obtained with the two lot structures are very similar. With the new lot structure, 20 lots would have been accepted at full pay, 7 lots would have been rejected, and twelve lots would have been accepted at reduced pay. The overall pay adjustments for the project were calculated to be 72.8 percent and 74.8 percent with the original lot structure and the revised lot structure, respectively. Again, these overall adjustments were calculated as an average pay adjustment, weighted for the number of sublots per lot. This calculation assumed that each sublot sample represented the same quantity of material. One would expect the overall payment to increase slightly under the modified lot structure. A common reason for stopping paving operations is due to problems found either visually or by inspection of sublot data. Under the system of enforcing four sublots, the poor results from a couple of sublots can affect the pay for a larger quantity of material, even if paving operations are not continued until another day. Under the revised system, the poor results are handled separately. If the material is rejected, the amount of material can be relatively small (e.g., 2 sublots) because paving operations were stopped.

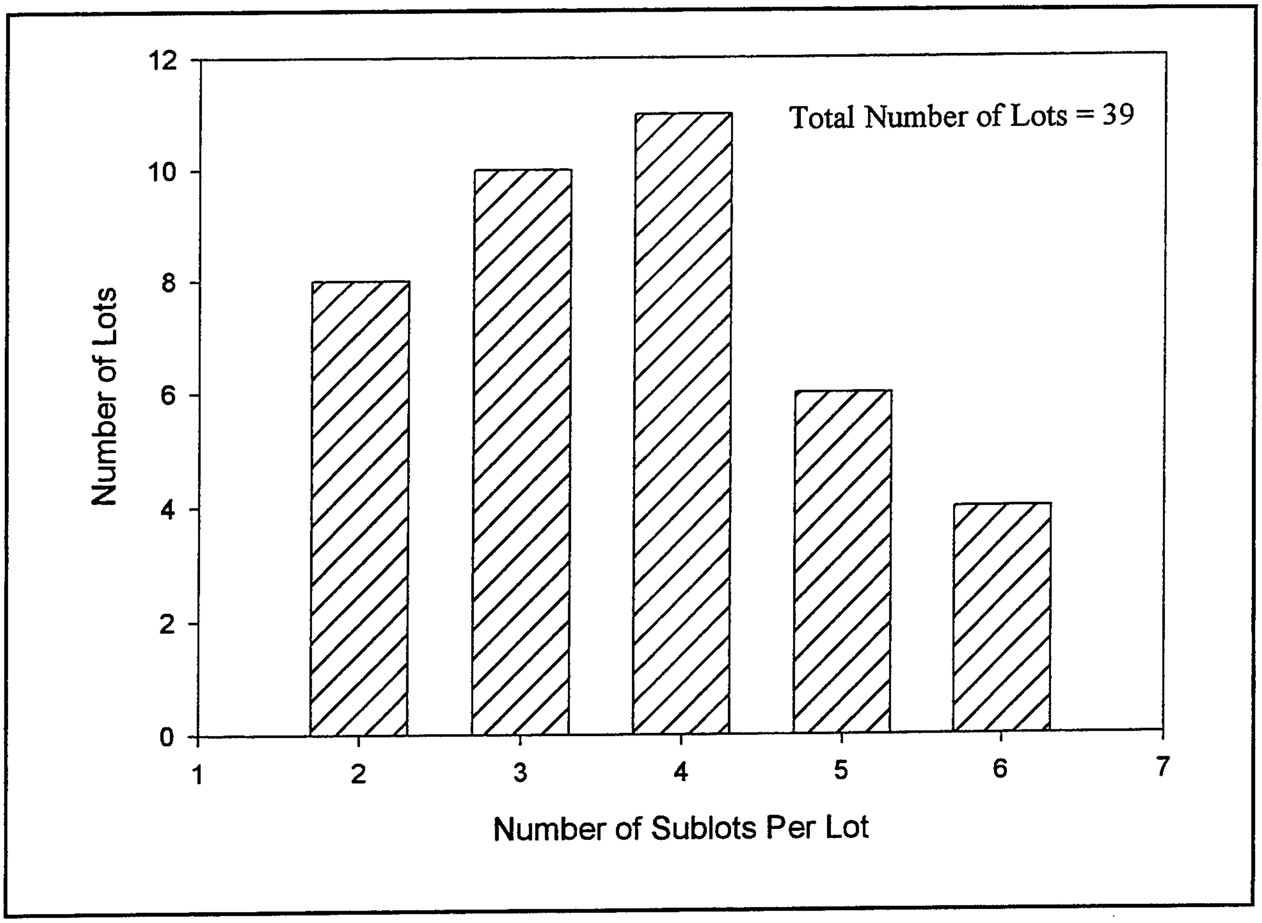

Figure 23. Frequencies for lot sizes when number of sublots per lot is flexible

Table 18
Job-Mix Formula for the Asphalt Concrete Surface Course

Material Characteristic	Specified Limits[1]	Job-Mix Formula
Sieve Size (measurement units = percent passing)		
19.0 mm	100	100
12.5 mm	82 - 96	90
9.5 mm	75 - 89	79
4.75 mm	59 - 73	65
2.36 mm	46 - 60	51
1.18 mm	34 - 48	35.5
0.60 mm	24 - 38	25.5
0.30 mm	13 - 27	16.5
0.15 mm	8 - 18	10
0.075 mm	3.0 - 6.0	6.0
Asphalt Cement Content (%)	N/A	6.1
Voids in Mineral Aggregate (%)	N/A	14
Marshall Stability (kN)	8.0 min.	16.8
Marshall Flow (0.25 mm)	16 max.	13
Voids Total Mix (%)	3 - 5	4.9
Voids Filled (%)	70 - 80	75
Laboratory-Compacted Bulk Specific Gravity	N/A	2.501
Calculated Theoretical Maximum Specific Gravity	N/A	2.630

[1] Army Technical Manual TM 5-822-8 (DA 1987).
N/A - no specified limits.

Table 19
Sublot Samples for Surface Course Material

Lot Number	Date and (Military Time) for Obtaining Truck Samples			
	Sublot #1	Sublot #2	Sublot #3	Sublot #4
1	8/15/87 (11:45)	8/16/87 (1:30)	8/16/87 (4:40)	8/16/87 (20:00)
2	8/16/87 (22:00)	8/17/87 (0:30)	8/17/87 (2:30)	8/17/87 (23:40)
3	8/18/87 (1:25)	8/18/87 (2:35)	8/19/87 (3:00)	N/A[1]
4	8/20/87 (19:55)	8/20/87 (21:10)	8/21/87 (19:30)	8/21/87 (21:15)
5	8/21/87 (22:40)	8/22/87 (1:55)	8/22/87 (20:00)	8/24/87 (20:30)
6	8/24/87 (22:30)	8/25/87 (2:15)	8/25/87 (19:40)	8/25/87 (22:25)
7	8/26/87 (1:15)	8/26/87 (22:25)	8/27/87 (0:20)	8/27/87 (19:55)
8	8/27/87 (21:55)	8/28/87 (18:30)	8/28/87 (20:30)	8/28/87 (22:05)
9	8/28/87 (23:45)	8/29/87 (1:30)	8/29/87 (3:05)	8/29/87 (19:55)
10	8/29/87 (21:40)	8/31/87 (18:30)	8/31/87 (20:30)	8/31/87 (22:00)
11	8/31/87 (23:50)	9/1/87 (1:35)	9/2/87 (20:55)	9/2/87 (22:45)
12	9/3/87 (1:25)	9/3/87 (21:15)	9/3/87 (22:35)	9/4/87 (1:05)
13	9/4/87 (22:10)	9/4/87 (23:00)	9/5/87 (21:00)	9/6/87 (2:00)
14	9/7/87 (0:05)	9/7/87 (1:30)	9/7/87 (19:45)	9/7/87 (21:30)
15	9/8/87 (0:35)	9/8/87 (21:15)	9/8/87 (23:05)	9/9/87 (1:30)
16	9/9/87 (21:15)	9/13/87 (18:45)	9/13/87 (20:40)	9/13/87 (23:50)
17	9/14/87 (2:05)	9/16/87 (18:35)	9/16/87 (20:20)	9/17/87 (20:40)
18	N/A[2]	N/A[3]	9/17/87 (22:25)	9/18/87 (0:25)
19	10/1/87 (21:25)	10/1/87 (23:15)	10/2/87 (1:15)	10/2/87 (3:30)
20	10/2/87 (21:00)	10/2/87 (23:00)	10/3/87 (1:45)	10/3/87 (4:10)
21	10/5/87 (19:15)	10/5/87 (21:30)	10/5/87 (0:30)	10/5/87 (3:30)
22	10/16/87 (20:30)	10/16/87 (22:15)	10/17/87 (0:25)	10/17/87 (1:40)
23	10/19/87 (19:15)	10/19/87 (21:00)	10/19/87 (23:00)	10/20/87 (0:45)
24	10/20/87 (3:10)	10/20/87 (4:30)	10/21/87 (18:35)	10/21/87 (20:20)
25	10/21/87 (23:30)	10/22/87 (1:05)	10/22/87 (18:10)	10/22/87 (20:00)
26	10/22/87 (22:05)	10/23/87 (0:00)	10/23/87 (3:30)	N/A[4]
27	10/29/87 (18:30)	10/29/87 (20:20)	10/29/87 (21:45)	10/30/87 (19:19)
28	10/30/87 (21:20)	10/30/87 (23:37)	10/31/87 (1:02)	10/31/87 (3:15)
29	11/2/87 (20:07)	11/2/87 (22:06)	11/2/87 (23:15)	11/3/87 (0:44)
30	11/3/87 (2:00)	11/3/87 (18:30)	11/3/87 (19:30)	11/3/87 (21:15)
31	11/3/87 (22:18)	11/4/87 (0:52)	11/4/87 (3:05)	11/4/87 (19:30)
32	11/4/87 (21:30)	11/4/87 (23:05)	11/5/87 (0:22)	11/5/87 (2:00)
33	11/5/87 (3:40)	11/5/87 (18:50)	11/5/87 (20:20)	N/A[5]
34	11/10/87 (19:10)	11/10/87 (20:40)	11/10/87 (23:04)	11/11/87 (0:45)
35	11/11/87 (2:15)	11/11/87 (18:20)	11/11/87 (19:25)	11/11/87 (22:16)
36	11/12/87 (0:46)	11/12/87 (4:00)	11/12/87 (20:02)	11/12/87 (23:35)
37	11/13/87 (15:50)	11/21/87 (10:30)	11/21/87 (12:23)	11/21/87 (17:00)
38	11/23/87 (10:19)	11/23/87 (15:26)	11/25/87 (15:40)	N/A[5]

[1] No truck sample; extraction and gradation performed on field core to force 4 sublots.
[2] No truck sample; reused data from 9/16/87 (20:20) to force 4 sublots.
[3] No truck sample; reused data from 9/17/87 (20:40) to force 4 sublots.
[4] No truck sample; reused data from 10/22/87 (20:00) to force 4 sublots.
[5] No data; applied acceptance criteria to 3 sublots.

Table 20
Summary of Acceptance Results for Surface Course Mixtures

Material Characteristic	Number of Lots					
	Current CEGS 02556			Modified CEGS 02556		
	Reject	(Pay Factor Range)	100% Pay	Reject	(Pay Factor Range)	100% Pay
Sieve Size						
19.0 mm	0	0	38	0	0	38
12.5 mm	0	3 (95-98)	35	0	2 (89.0-93.7)	36
9.5 mm	0	14 (90-98)	24	0	2 (65.0-83.8)	36
4.75 mm	0	12 (90-98)	26	2	1 (90.3)	35
2.36 mm	0	13 (90-98)	25	1	1 (94.4)	36
1.18 mm	1	13 (90-98)	24	0	1 (99.8)	37
0.60 mm	0	15 (90-98)	23	0	0	38
0.30 mm	0	3 (98)	35	0	0	38
0.15 mm	0	24 (95-98)	14	0	0	38
0.075 mm	0	11 (90-98)	27	0	0	38
Asphalt Cement Content	1	11 (90-98)	26	2	5 (76.9-86.9)	31
Mat Density	6	24 (75.0-99.9)	8	5	6 (79.3-96.7)	28
Joint Density	2	14 (80.6-99.9)	12	1	1 (88.9)	36
Overall	8	30 (75.0-98.0)	0	9	12 (76.9-96.7)	17

Table 21
Sublot Samples With Flexible Lot Sizes

Lot No.	Date and (Military Time) for Obtaining Truck Samples					
	Sublot #1	Sublot #2	Sublot #3	Sublot #4	Sublot #5	Sublot #6
1	8/16 (1:30)	8/16 (4:40)	[1]	[1]	[1]	[1]
2	8/16 (20:00)	8/16 (22:00)	8/17 (0:30)	8/17 (2:30)	[1]	[1]
3	8/17 (23:40)	8/18 (1:25)	8/18 (2:35)	8/19 (3:00)	[1]	[1]
4	8/20 (19:55)	8/20 (21:10)	[1]	[1]	[1]	[1]
5	8/21 (19:30)	8/21 (21:15)	8/21 (22:40)	8/22 (1:55)	[1]	[1]
6	8/22 (20:00)	8/24 (20:30)	8/24 (22:30)	8/25 (2:15)	[1]	[1]
7	8/25 (19:40)	8/25 (22:25)	8/26 (1:15)	[1]	[1]	[1]
8	8/26 (22:25)	8/27 (0:20)	[1]	[1]	[1]	[1]
9	8/27 (19:55)	8/27 (21:55)	[1]	[1]	[1]	[1]
10	8/28 (18:30)	8/28 (20:30)	8/28 (22:05)	8/28 (23:45)	8/29 (1:30)	8/29 (3:05)
11	8/29 (19:55)	8/29 (21:40)	[1]	[1]	[1]	[1]
12	8/31 (18:30)	8/31 (20:30)	8/31 (22:00)	8/31 (23:50)	9/1 (1:35)	[1]
13	9/2 (20:55)	9/2 (22:45)	9/3 (1:25)	[1]	[1]	[1]
14	9/3 (21:15)	9/3 (22:35)	9/4 (1:05)	[1]	[1]	[1]
15	9/4 (22:10)	9/4 (23:00)	9/5 (21:00)	9/6 (2:00)	[1]	[1]
16	9/7 (0:05)	9/7 (1:30)	[1]	[1]	[1]	[1]
17	9/7 (19:45)	9/7 (21:30)	9/8 (0:35)	[1]	[1]	[1]
18	9/8 (21:15)	9/8 (23:05)	9/9 (1:30)	[1]	[1]	[1]
19	9/13 (18:45)	9/13 (20:40)	9/13 (23:50)	9/14 (2:05)	[1]	[1]
20	9/16 (18:35)	9/16 (20:20)	[1]	[1]	[1]	[1]
21	9/17 (20:40)	9/17 (22:25)	9/18 (0:25)	[1]	[1]	[1]
22	10/1 (21:25)	10/1 (23:15)	10/2 (1:15)	10/2 (3:30)	[1]	[1]
23	10/2 (21:00)	10/2 (23:00)	10/3 (1:45)	10/3 (4:10)	[1]	[1]
24	10/5 (19:15)	10/5 (21:30)	10/5 (0:30)	10/5 (3:30)	[1]	[1]
25	10/16 (20:30)	10/16 (22:15)	10/17 (0:25)	10/17 (1:40)	[1]	[1]
26	10/19 (19:15)	10/19 (21:00)	10/19 (23:00)	10/20 (0:45)	10/20 (3:10)	10/20 (4:30)
27	10/21 (18:35)	10/21 (20:20)	10/21 (23:30)	10/22 (1:05)	[1]	[1]
28	10/22 (18:10)	10/22 (20:00)	10/22 (22:05)	10/23 (0:00)	10/23 (3:30)	[1]
29	10/29 (18:30)	10/29 (20:20)	10/29 (21:45)	[1]	[1]	[1]
30	10/30 (19:19)	10/30 (21:20)	10/30 (23:37)	10/31 (1:02)	10/31 (3:15)	[1]
31	11/2 (20:07)	11/2 (22:06)	11/2 (23:15)	11/3 (0:44)	11/3 (2:00)	[1]
32	11/3 (18:30)	11/3 (19:30)	11/3 (21:15)	11/3 (22:18)	11/4 (0:52)	11/4 (3:05)
33	11/4 (19:30)	11/4 (21:30)	11/4 (23:05)	11/5 (0:22)	11/5 (2:00)	11/5 (3:40)
34	11/5 (18:50)	11/5 (20:20)	[1]	[1]	[1]	[1]
35	11/10 (19:10)	11/10 (20:40)	11/10 (23:04)	11/11 (0:45)	11/11 (2:15)	[1]
36	11/11 (18:20)	11/11 (19:25)	11/11 (22:16)	11/12 (0:46)	11/12 (4:00)	[1]
37	11/12 (20:02)	11/12 (23:35)	11/13 (15:50)	[1]	[1]	[1]
38	11/21 (10:30)	11/21 (12:23)	11/21 (17:00)	[1]	[1]	[1]
39	11/23 (10:19)	11/23 (15:26)	11/25 (15:40)	[1]	[1]	[1]

[1] No entry; the lot had fewer sublots.

Table 22
Comparison of Acceptance Results for Surface Course Mixtures

Material Characteristic	Number of Lots					
	Modified CEGS 02556 with Lots Separated to Achieve 4 Sublots			Modified CEGS 02556 with Flexible Number of Sublots		
	Reject	Pay Factor (range)	100% Pay	Reject	Pay Factor (range)	100% Pay
Sieve Size						
19.0 mm	0	0	38	0	0	39
12.5 mm	0	2 (89.0-93.7)	36	0	1 (96.6)	38
9.5 mm	0	2 (65.0-83.8)	36	0	3 (67.1-90.8)	36
4.75 mm	2	1 (90.3)	35	0	4 (72.5-94.7)	35
2.36 mm	1	1 (94.4)	36	0	1 (81.4)	38
1.18 mm	0	1 (99.8)	37	0	0	39
0.60 mm	0	0	38	0	0	39
0.30 mm	0	0	38	0	0	39
0.15 mm	0	0	38	0	0	39
0.075 mm	0	0	38	0	0	39
Asphalt Cement Content	2	5 (76.9-86.9)	31	2	5 (77.3-96.5)	32
Mat Density	5	6 (79.3-96.7)	28	4	6 (71.1-91.1)	29
Joint Density	1	1 (88.9)	36	1	1 (90.3)	37
Overall	9	12 (76.9-96.7)	17	7	12 (71.1-95.6)	20

9 Summary and Recommendations

Summary

Statistical acceptance plans offer several advantages for construction specifications. During the development of criteria, inherent variability in sampling and testing can be considered explicitly. Risks for contractual parties, necessitated by basing judgements on samples of data, can be estimated and compared to ensure fairness. Process control plans can be developed with the same theories of probability as the acceptance plans and thus, can have improved usefulness and accuracy. Logical pay adjustments can be developed using the estimated distributions of material characteristic data.

The statistical acceptance plan developed in this report is intended as a modification for CEGS 02556, "Asphaltic Bituminous Heavy-Duty Pavement (Central-Plant Hot Mix)" (USACE 1991). The modification can be implemented with the proposed Engineering Technical Letter, included in this report as Appendix D. The modifications are primarily directed towards acceptance procedures, with only minor modifications to other aspects of the guide specification, such as the sampling plan.

The proposed statistical acceptance plan bases material acceptance on calculations of "fraction nonconforming." Fraction nonconforming for a material characteristic refers to the portion of its probability distribution that falls outside of specification limits. This approach is similar to the approaches used by the Federal Highway Administration and the Federal Aviation Administration. The use of acceptance procedures that are similar to those used by other transportation agencies offers advantages in terms of facilitating contractor familiarity with pavement specifications. A single contractor, who could work for any of the three agencies, would have improved understanding and confidence in a specification format that was uniform from job to job.

The statistical acceptance plan was applied to actual quality assurance data obtained from an airfield paving project. The statistical acceptance plan was shown to be able to identify poor-quality material with a level of discrimination similar to the acceptance plan included in the existing pavement specification. In this comparison, the statistical acceptance plan provided two additional advantages over current acceptance procedures. First, even though overall

project payment adjustments were comparable, the statistical acceptance plan imposed payment adjustments to far fewer lots. The current acceptance procedure can cause contractors to feel "nickel-and-dimed" and to feel that all requirements can not possibly be met. Secondly, the statistical acceptance plan was shown to provide flexibility in terms of the number of samples obtained per lot. Under the current procedure, four sublots must be obtained for each lot. In order to achieve this, sublots from different days and from different areas of an airfield must be combined. This causes confusion and also decreases the homogeneity of lots, which is contrary to the rules commonly stated for establishing lots within a production process.

Recommendations

The statistical acceptance plan should be applied to quality assurance data obtained from several additional completed projects, in a manner similar to that demonstrated in this report. The selected projects should represent a wide range of workmanship qualities. This effort will provide informative comparisons between the current acceptance plan and the proposed statistical acceptance plan. Comparisons would include the resulting lot and sublot structures, the overall contractor payments, and the distribution of payment reductions among the different quality assurance components. This effort will also identify any implementation problems with the newly-developed plan.

This study did not address the development of statistical process control procedures. These procedures would be a useful addition to this study and would be of benefit to contractors trying to meet the criteria imposed by the statistical acceptance plan. The development of statistical process control procedures should be initiated as a follow-up study.

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Appendix A
Statistical Reference Tables

Table A1
Probability of a Obtaining a Random Value of Z Greater Than the Values Shown in the Margins (after Steel and Torrie 1980)

z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	.5000	.4960	.4920	.4880	.4840	.4801	.4761	.4721	.4681	.4641
0.1	.4602	.4562	.4522	.4483	.4443	.4404	.4364	.4325	.4286	.4247
0.2	.4207	.4168	.4129	.4090	.4052	.4013	.3974	.3936	.3897	.3859
0.3	.3821	.3783	.3745	.3707	.3669	.3632	.3594	.3557	.3520	.3483
0.4	.3446	.3409	.3372	.3336	.3300	.3264	.3228	.3192	.3156	.3121
0.5	.3085	.3050	.3015	.2981	.2946	.2912	.2877	.2843	.2810	.2776
0.6	.2743	.2709	.2676	.2643	.2611	.2578	.2546	.2514	.2483	.2451
0.7	.2420	.2389	.2358	.2327	.2296	.2266	.2236	.2206	.2177	.2148
0.8	.2119	.2090	.2061	.2033	.2005	.1977	.1949	.1922	.1894	.1867
0.9	.1841	.1814	.1788	.1762	.1736	.1711	.1685	.1660	.1635	.1611
1.0	.1587	.1562	.1539	.1515	.1492	.1469	.1446	.1423	.1401	.1379
1.1	.1357	.1335	.1314	.1292	.1271	.1251	.1230	.1210	.1190	.1170
1.2	.1151	.1131	.1112	.1093	.1075	.1056	.1038	.1020	.1003	.0985
1.3	.0968	.0951	.0934	.0918	.0901	.0885	.0869	.0853	.0838	.0823
1.4	.0808	.0793	.0078	.0764	.0749	.0735	.0721	.0708	.0694	.0681
1.5	.0668	.0655	.0643	.0630	.0618	.0606	.0594	.0582	.0571	.0559
1.6	.0548	.0537	.0526	.0516	.0505	.0495	.0485	.0475	.0465	.0455
1.7	.0446	.0436	.0427	.0418	.0409	.0401	.0392	.0384	.0375	.0367
1.8	.0359	.0351	.0344	.0336	.0329	.0322	.0314	.0307	.0301	.0294
1.9	.0287	.0281	.0274	.0268	.0262	.0256	.0250	.0244	.0239	.0233
2.0	.0228	.0222	.0217	.0212	.0207	.0202	.0197	.0192	.0188	.0183
2.1	.0179	.0174	.0170	.0166	.0162	.0158	.0154	.0150	.0146	.0143
2.2	.0139	.0136	.0132	.0129	.0125	.0122	.0119	.0116	.0113	.0110
2.3	.0107	.0104	.0102	.0099	.0096	.0094	.0091	.0089	.0087	.0084
2.4	.0082	.0080	.0078	.0075	.0073	.0071	.0069	.0068	.0066	.0064
2.5	.0062	.0060	.0059	.0057	.0055	.0054	.0052	.0051	.0049	.0048
2.6	.0047	.0045	.0044	.0043	.0041	.0040	.0039	.0038	.0037	.0036
2.7	.0035	.0034	.0033	.0032	.0031	.0030	.0029	.0028	.0027	.0026
2.8	.0026	.0025	.0024	.0023	.0023	.0022	.0021	.0021	.0020	.0019
2.9	.0019	.0018	.0018	.0017	.0016	.0016	.0015	.0015	.0014	.0014
3.0	.0013	.0013	.0013	.0012	.0012	.0011	.0011	.0011	.0010	.0010
3.1	.0010	.0009	.0009	.0009	.0008	.0008	.0008	.0008	.0007	.0007
3.2	.0007	.0007	.0006	.0006	.0006	.0006	.0006	.0005	.0005	.0005
3.3	.0005	.0005	.0005	.0004	.0004	.0004	.0004	.0004	.0004	.0003
3.4	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0002
3.6	.0002	.0002	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001

Table A2
Values of t (after Fisher and Yates 1949)

df	Probability of a Numerically Larger Value of t (Two-Tail Test)				
	0.1	0.05	0.02	0.01	0.001
1	6.314	12.706	31.821	63.657	636.619
2	2.920	4.303	6.965	9.925	31.598
3	2.353	3.182	4.541	5.841	12.941
4	2.132	2.776	3.747	4.604	8.610
5	2.015	2.571	3.365	4.032	6.859
6	1.943	2.447	3.143	3.707	5.959
7	1.895	2.365	2.998	3.499	5.405
8	1.860	2.306	2.896	3.355	5.041
9	1.833	2.262	2.821	3.250	4.781
10	1.812	2.228	2.764	3.169	4.587
11	1.796	2.201	2.718	3.106	4.437
12	1.782	2.179	2.681	3.055	4.318
13	1.771	2.160	2.650	3.012	4.221
14	1.761	2.145	2.624	2.977	4.140
15	1.753	2.131	2.602	2.947	4.073
16	1.746	2.120	2.583	2.921	4.015
17	1.740	2.110	2.567	2.898	3.965
18	1.734	2.101	2.552	2.878	3.922
19	1.729	2.093	2.539	2.861	3.883
20	1.725	2.086	2.528	2.845	3.850
21	1.721	2.080	2.518	2.831	3.819
22	1.717	2.074	2.508	2.819	3.792
23	1.714	2.069	2.500	2.807	3.767
24	1.711	2.064	2.492	2.797	3.745
25	1.708	2.060	2.485	2.787	3.725
26	1.706	2.056	2.479	2.779	3.707
27	1.703	2.052	2.473	2.771	3.690
28	1.701	2.048	2.467	2.763	3.674
29	1.699	2.045	2.462	2.756	3.659
30	1.697	2.042	2.457	2.750	3.646
40	1.684	2.021	2.423	2.704	3.551
60	1.671	2.000	2.390	2.660	3.460
120	1.658	1.980	2.358	2.617	3.373
∞	1.645	1.960	2.326	2.576	3.291
df	0.05	0.025	0.01	0.005	0.0005
	Probability of a Larger Positive Value of t (One-Tail Test)				

Table A3
Fraction Nonconforming Based on Quality Index Values (after ASQC 1980)

Q_U or Q_L	Sample Size								
	2	3	4	5	6	8	10	12	100
0.00	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
0.01	0.497	0.497	0.497	0.496	0.496	0.496	0.496	0.496	0.496
0.02	0.495	0.494	0.493	0.493	0.493	0.492	0.492	0.492	0.492
0.03	0.492	0.492	0.490	0.489	0.489	0.489	0.488	0.488	0.488
0.04	0.489	0.489	0.487	0.486	0.485	0.485	0.485	0.485	0.484
0.05	0.487	0.486	0.483	0.482	0.482	0.481	0.481	0.481	0.480
0.06	0.484	0.483	0.480	0.479	0.478	0.477	0.477	0.477	0.476
0.07	0.481	0.481	0.477	0.475	0.474	0.474	0.473	0.473	0.472
0.08	0.478	0.478	0.473	0.472	0.471	0.470	0.469	0.469	0.468
0.09	0.476	0.475	0.470	0.468	0.467	0.466	0.465	0.465	0.464
0.10	0.473	0.472	0.467	0.464	0.463	0.462	0.462	0.461	0.460
0.11	0.470	0.470	0.463	0.461	0.460	0.458	0.458	0.457	0.456
0.12	0.467	0.467	0.460	0.457	0.456	0.455	0.454	0.454	0.452
0.13	0.465	0.464	0.457	0.454	0.452	0.451	0.450	0.450	0.448
0.14	0.462	0.461	0.453	0.450	0.449	0.447	0.446	0.446	0.444
0.15	0.459	0.459	0.450	0.447	0.445	0.443	0.443	0.442	0.441
0.16	0.456	0.456	0.447	0.443	0.441	0.440	0.439	0.438	0.437
0.17	0.453	0.453	0.443	0.440	0.438	0.436	0.435	0.434	0.433
0.18	0.451	0.450	0.440	0.436	0.434	0.432	0.431	0.431	0.429
0.19	0.448	0.447	0.437	0.433	0.430	0.428	0.427	0.427	0.425
0.20	0.445	0.445	0.433	0.429	0.427	0.425	0.424	0.423	0.421
0.21	0.442	0.442	0.430	0.425	0.423	0.421	0.420	0.419	0.417
0.22	0.439	0.439	0.427	0.422	0.419	0.417	0.416	0.415	0.413
0.23	0.436	0.436	0.423	0.418	0.416	0.413	0.412	0.412	0.409
0.24	0.433	0.433	0.420	0.415	0.412	0.410	0.408	0.408	0.405
0.25	0.430	0.431	0.417	0.411	0.409	0.406	0.405	0.404	0.402
0.26	0.427	0.428	0.413	0.408	0.405	0.402	0.401	0.400	0.398
0.27	0.424	0.425	0.410	0.404	0.401	0.399	0.397	0.396	0.394
0.28	0.421	0.422	0.407	0.401	0.398	0.395	0.393	0.393	0.390
0.29	0.418	0.419	0.403	0.397	0.394	0.391	0.390	0.389	0.386
0.30	0.415	0.416	0.400	0.394	0.391	0.387	0.386	0.385	0.382
0.31	0.412	0.413	0.397	0.390	0.387	0.384	0.382	0.381	0.379
0.32	0.409	0.411	0.393	0.387	0.383	0.380	0.379	0.378	0.375
0.33	0.406	0.408	0.390	0.383	0.380	0.376	0.375	0.374	0.371
0.34	0.402	0.405	0.387	0.380	0.376	0.373	0.371	0.370	0.367

(Sheet 1 of 9)

Table A3 (Continued)									
	Sample Size								
Q_U or Q_L	2	3	4	5	6	8	10	12	100
0.35	0.399	0.402	0.383	0.376	0.373	0.369	0.368	0.367	0.363
0.36	0.396	0.399	0.380	0.373	0.369	0.366	0.364	0.363	0.360
0.37	0.392	0.396	0.377	0.369	0.366	0.362	0.360	0.359	0.356
0.38	0.389	0.393	0.373	0.366	0.362	0.358	0.357	0.356	0.352
0.39	0.385	0.390	0.370	0.362	0.358	0.355	0.353	0.352	0.349
0.40	0.382	0.387	0.367	0.359	0.355	0.351	0.349	0.348	0.345
0.41	0.378	0.384	0.363	0.355	0.351	0.348	0.346	0.345	0.341
0.42	0.374	0.382	0.360	0.352	0.348	0.344	0.342	0.341	0.338
0.43	0.371	0.379	0.357	0.348	0.344	0.340	0.338	0.337	0.334
0.44	0.367	0.376	0.353	0.345	0.341	0.337	0.335	0.334	0.330
0.45	0.363	0.373	0.350	0.342	0.337	0.333	0.331	0.330	0.327
0.46	0.359	0.370	0.347	0.338	0.334	0.330	0.328	0.327	0.323
0.47	0.355	0.367	0.343	0.335	0.330	0.326	0.324	0.323	0.320
0.48	0.350	0.364	0.340	0.331	0.327	0.323	0.321	0.320	0.316
0.49	0.346	0.361	0.337	0.328	0.323	0.319	0.317	0.316	0.312
0.50	0.342	0.357	0.333	0.324	0.320	0.316	0.314	0.313	0.309
0.51	0.337	0.354	0.330	0.321	0.317	0.312	0.310	0.309	0.305
0.52	0.332	0.351	0.327	0.318	0.313	0.309	0.307	0.306	0.302
0.53	0.327	0.348	0.323	0.314	0.310	0.305	0.303	0.302	0.298
0.54	0.322	0.345	0.320	0.311	0.306	0.302	0.300	0.299	0.295
0.55	0.317	0.342	0.317	0.307	0.303	0.298	0.296	0.295	0.292
0.56	0.311	0.339	0.313	0.304	0.299	0.295	0.293	0.292	0.288
0.57	0.306	0.336	0.310	0.301	0.296	0.292	0.290	0.288	0.285
0.58	0.299	0.332	0.307	0.297	0.293	0.288	0.286	0.285	0.281
0.59	0.293	0.329	0.303	0.294	0.289	0.285	0.283	0.282	0.278
0.60	0.286	0.326	0.300	0.291	0.286	0.281	0.279	0.278	0.275
0.61	0.279	0.323	0.297	0.287	0.283	0.278	0.276	0.275	0.271
0.62	0.271	0.320	0.293	0.284	0.279	0.275	0.273	0.272	0.268
0.63	0.263	0.316	0.290	0.281	0.276	0.271	0.269	0.268	0.265
0.64	0.254	0.313	0.287	0.277	0.273	0.268	0.266	0.265	0.261
0.65	0.243	0.310	0.283	0.274	0.269	0.265	0.263	0.262	0.258
0.66	0.232	0.306	0.280	0.271	0.266	0.262	0.260	0.258	0.255
0.67	0.218	0.303	0.277	0.267	0.263	0.258	0.256	0.255	0.252
0.68	0.201	0.300	0.273	0.264	0.259	0.255	0.253	0.252	0.249
0.69	0.179	0.296	0.270	0.261	0.256	0.252	0.250	0.249	0.245
									(Sheet 2 of 9)

Table A3 (Continued)									
	Sample Size								
Q_U or Q_L	**2**	**3**	**4**	**5**	**6**	**8**	**10**	**12**	**100**
0.70	0.144	0.293	0.267	0.257	0.253	0.249	0.247	0.246	0.242
0.71	0.000	0.289	0.263	0.254	0.250	0.245	0.244	0.242	0.239
0.72	0.000	0.286	0.260	0.251	0.246	0.242	0.240	0.239	0.236
0.73	0.000	0.282	0.257	0.248	0.243	0.239	0.237	0.236	0.233
0.74	0.000	0.279	0.253	0.244	0.240	0.236	0.234	0.233	0.230
0.75	0.000	0.275	0.250	0.241	0.237	0.233	0.231	0.230	0.227
0.76	0.000	0.271	0.247	0.238	0.234	0.230	0.228	0.227	0.224
0.77	0.000	0.268	0.243	0.235	0.231	0.227	0.225	0.224	0.221
0.78	0.000	0.264	0.240	0.231	0.227	0.224	0.222	0.221	0.218
0.79	0.000	0.260	0.237	0.228	0.224	0.220	0.219	0.218	0.215
0.80	0.000	0.256	0.233	0.225	0.221	0.217	0.216	0.215	0.212
0.81	0.000	0.253	0.230	0.222	0.218	0.214	0.213	0.212	0.209
0.82	0.000	0.249	0.227	0.219	0.215	0.211	0.210	0.209	0.206
0.83	0.000	0.245	0.223	0.216	0.212	0.208	0.207	0.206	0.203
0.84	0.000	0.241	0.220	0.212	0.209	0.205	0.204	0.203	0.201
0.85	0.000	0.237	0.217	0.209	0.206	0.202	0.201	0.200	0.198
0.86	0.000	0.233	0.213	0.206	0.203	0.200	0.198	0.197	0.195
0.87	0.000	0.228	0.210	0.203	0.200	0.197	0.195	0.194	0.192
0.88	0.000	0.224	0.207	0.200	0.197	0.194	0.192	0.192	0.190
0.89	0.000	0.220	0.203	0.197	0.194	0.191	0.190	0.189	0.187
0.90	0.000	0.216	0.200	0.194	0.191	0.188	0.187	0.186	0.184
0.91	0.000	0.211	0.197	0.191	0.188	0.185	0.184	0.183	0.182
0.92	0.000	0.207	0.193	0.188	0.185	0.182	0.181	0.181	0.179
0.93	0.000	0.202	0.190	0.185	0.182	0.179	0.178	0.178	0.176
0.94	0.000	0.197	0.187	0.182	0.179	0.177	0.176	0.175	0.174
0.95	0.000	0.192	0.183	0.179	0.176	0.174	0.173	0.172	0.171
0.96	0.000	0.188	0.180	0.176	0.173	0.171	0.170	0.170	0.169
0.97	0.000	0.183	0.177	0.173	0.170	0.168	0.168	0.167	0.166
0.98	0.000	0.177	0.173	0.170	0.168	0.166	0.165	0.165	0.164
0.99	0.000	0.172	0.170	0.167	0.165	0.163	0.162	0.162	0.161
1.00	0.000	0.167	0.167	0.164	0.162	0.160	0.160	0.159	0.159
1.01	0.000	0.161	0.163	0.161	0.159	0.158	0.157	0.157	0.156
1.02	0.000	0.155	0.160	0.158	0.156	0.155	0.155	0.154	0.154
1.03	0.000	0.149	0.157	0.155	0.154	0.153	0.152	0.152	0.151
1.04	0.000	0.143	0.153	0.152	0.151	0.150	0.150	0.149	0.149
1.05	0.000	0.137	0.150	0.149	0.148	0.147	0.147	0.147	0.147

(Sheet 3 of 9)

Table A3 (Continued)

Q_U or Q_L	Sample Size								
	2	3	4	5	6	8	10	12	100
1.06	0.000	0.130	0.147	0.146	0.146	0.145	0.145	0.144	0.145
1.07	0.000	0.123	0.143	0.143	0.143	0.142	0.142	0.142	0.142
1.08	0.000	0.115	0.140	0.140	0.140	0.140	0.140	0.140	0.140
1.09	0.000	0.107	0.137	0.138	0.138	0.137	0.137	0.137	0.138
1.10	0.000	0.098	0.133	0.135	0.135	0.135	0.135	0.135	0.136
1.11	0.000	0.089	0.130	0.132	0.132	0.133	0.133	0.133	0.133
1.12	0.000	0.078	0.127	0.129	0.130	0.130	0.130	0.130	0.131
1.13	0.000	0.066	0.123	0.126	0.127	0.128	0.128	0.128	0.129
1.14	0.000	0.051	0.120	0.124	0.125	0.125	0.126	0.126	0.127
1.15	0.000	0.029	0.117	0.121	0.122	0.123	0.123	0.124	0.125
1.16	0.000	0.000	0.113	0.118	0.120	0.121	0.121	0.121	0.123
1.17	0.000	0.000	0.110	0.116	0.117	0.118	0.119	0.119	0.121
1.18	0.000	0.000	0.107	0.113	0.115	0.116	0.117	0.117	0.119
1.19	0.000	0.000	0.103	0.110	0.112	0.114	0.115	0.115	0.117
1.20	0.000	0.000	0.100	0.108	0.110	0.112	0.112	0.113	0.115
1.21	0.000	0.000	0.097	0.105	0.107	0.109	0.110	0.111	0.113
1.22	0.000	0.000	0.093	0.102	0.105	0.107	0.108	0.109	0.111
1.23	0.000	0.000	0.090	0.100	0.103	0.105	0.106	0.107	0.109
1.24	0.000	0.000	0.087	0.097	0.100	0.103	0.104	0.105	0.107
1.25	0.000	0.000	0.083	0.095	0.098	0.101	0.102	0.103	0.105
1.26	0.000	0.000	0.080	0.092	0.096	0.099	0.100	0.101	0.104
1.27	0.000	0.000	0.077	0.090	0.094	0.097	0.098	0.099	0.102
1.28	0.000	0.000	0.073	0.087	0.091	0.095	0.096	0.097	0.100
1.29	0.000	0.000	0.070	0.085	0.089	0.093	0.094	0.095	0.098
1.30	0.000	0.000	0.067	0.082	0.087	0.091	0.092	0.093	0.096
1.31	0.000	0.000	0.063	0.080	0.085	0.089	0.090	0.091	0.095
1.32	0.000	0.000	0.060	0.077	0.083	0.087	0.088	0.089	0.093
1.33	0.000	0.000	0.057	0.075	0.080	0.085	0.087	0.088	0.091
1.34	0.000	0.000	0.053	0.073	0.078	0.083	0.085	0.086	0.090
1.35	0.000	0.000	0.050	0.070	0.076	0.081	0.083	0.084	0.088
1.36	0.000	0.000	0.047	0.068	0.074	0.079	0.081	0.082	0.086
1.37	0.000	0.000	0.043	0.066	0.072	0.077	0.079	0.081	0.085
1.38	0.000	0.000	0.040	0.063	0.070	0.076	0.078	0.079	0.083
1.39	0.000	0.000	0.037	0.061	0.068	0.074	0.076	0.077	0.082
1.40	0.000	0.000	0.033	0.059	0.066	0.072	0.074	0.076	0.080
1.41	0.000	0.000	0.030	0.057	0.064	0.070	0.073	0.074	0.079

(Sheet 4 of 9)

Table A3 (Continued)									
	Sample Size								
Q_U or Q_L	2	3	4	5	6	8	10	12	100
1.42	0.000	0.000	0.027	0.054	0.062	0.068	0.071	0.072	0.077
1.43	0.000	0.000	0.023	0.052	0.061	0.067	0.069	0.071	0.076
1.44	0.000	0.000	0.020	0.050	0.059	0.065	0.068	0.069	0.074
1.45	0.000	0.000	0.017	0.048	0.057	0.063	0.066	0.068	0.073
1.46	0.000	0.000	0.013	0.046	0.055	0.062	0.065	0.066	0.072
1.47	0.000	0.000	0.010	0.044	0.053	0.060	0.063	0.065	0.070
1.48	0.000	0.000	0.007	0.042	0.052	0.059	0.062	0.063	0.069
1.49	0.000	0.000	0.003	0.040	0.050	0.057	0.060	0.062	0.068
1.50	0.000	0.000	0.000	0.038	0.048	0.056	0.059	0.060	0.066
1.51	0.000	0.000	0.000	0.036	0.046	0.054	0.057	0.059	0.065
1.52	0.000	0.000	0.000	0.034	0.045	0.053	0.056	0.058	0.064
1.53	0.000	0.000	0.000	0.032	0.043	0.051	0.055	0.056	0.062
1.54	0.000	0.000	0.000	0.030	0.042	0.050	0.053	0.055	0.061
1.55	0.000	0.000	0.000	0.029	0.040	0.048	0.052	0.054	0.060
1.56	0.000	0.000	0.000	0.027	0.038	0.047	0.050	0.052	0.059
1.57	0.000	0.000	0.000	0.025	0.037	0.046	0.049	0.051	0.058
1.58	0.000	0.000	0.000	0.024	0.035	0.044	0.048	0.050	0.056
1.59	0.000	0.000	0.000	0.022	0.034	0.043	0.047	0.049	0.055
1.60	0.000	0.000	0.000	0.020	0.033	0.042	0.045	0.047	0.054
1.61	0.000	0.000	0.000	0.019	0.031	0.040	0.044	0.046	0.053
1.62	0.000	0.000	0.000	0.017	0.030	0.039	0.043	0.045	0.052
1.63	0.000	0.000	0.000	0.016	0.028	0.038	0.042	0.044	0.051
1.64	0.000	0.000	0.000	0.014	0.027	0.037	0.041	0.043	0.050
1.65	0.000	0.000	0.000	0.013	0.026	0.035	0.039	0.042	0.049
1.66	0.000	0.000	0.000	0.011	0.025	0.034	0.038	0.041	0.048
1.67	0.000	0.000	0.000	0.010	0.023	0.033	0.037	0.040	0.047
1.68	0.000	0.000	0.000	0.009	0.022	0.032	0.036	0.038	0.046
1.69	0.000	0.000	0.000	0.008	0.021	0.031	0.035	0.037	0.045
1.70	0.000	0.000	0.000	0.007	0.020	0.030	0.034	0.036	0.044
1.71	0.000	0.000	0.000	0.006	0.019	0.029	0.033	0.035	0.043
1.72	0.000	0.000	0.000	0.005	0.018	0.028	0.032	0.034	0.042
1.73	0.000	0.000	0.000	0.004	0.017	0.027	0.031	0.034	0.041
1.74	0.000	0.000	0.000	0.003	0.016	0.026	0.030	0.033	0.040
1.75	0.000	0.000	0.000	0.002	0.015	0.025	0.029	0.032	0.039
1.76	0.000	0.000	0.000	0.001	0.014	0.024	0.028	0.031	0.038
1.77	0.000	0.000	0.000	0.001	0.013	0.023	0.027	0.030	0.038

(Sheet 5 of 9)

Table A3 (Continued)									
	Sample Size								
Q_U or Q_L	2	3	4	5	6	8	10	12	100
1.78	0.000	0.000	0.000	0.000	0.012	0.022	0.027	0.029	0.037
1.79	0.000	0.000	0.000	0.000	0.011	0.021	0.026	0.028	0.036
1.80	0.000	0.000	0.000	0.000	0.010	0.020	0.025	0.027	0.035
1.81	0.000	0.000	0.000	0.000	0.009	0.020	0.024	0.027	0.034
1.82	0.000	0.000	0.000	0.000	0.008	0.019	0.023	0.026	0.034
1.83	0.000	0.000	0.000	0.000	0.008	0.018	0.022	0.025	0.033
1.84	0.000	0.000	0.000	0.000	0.007	0.017	0.022	0.024	0.032
1.85	0.000	0.000	0.000	0.000	0.006	0.017	0.021	0.023	0.031
1.86	0.000	0.000	0.000	0.000	0.006	0.016	0.020	0.023	0.031
1.87	0.000	0.000	0.000	0.000	0.005	0.015	0.020	0.022	0.030
1.88	0.000	0.000	0.000	0.000	0.005	0.014	0.019	0.021	0.029
1.89	0.000	0.000	0.000	0.000	0.004	0.014	0.018	0.021	0.029
1.90	0.000	0.000	0.000	0.000	0.004	0.013	0.017	0.020	0.028
1.91	0.000	0.000	0.000	0.000	0.003	0.012	0.017	0.019	0.027
1.92	0.000	0.000	0.000	0.000	0.003	0.012	0.016	0.019	0.027
1.93	0.000	0.000	0.000	0.000	0.002	0.011	0.016	0.018	0.026
1.94	0.000	0.000	0.000	0.000	0.002	0.011	0.015	0.017	0.025
1.95	0.000	0.000	0.000	0.000	0.001	0.010	0.014	0.017	0.025
1.96	0.000	0.000	0.000	0.000	0.001	0.010	0.014	0.016	0.024
1.97	0.000	0.000	0.000	0.000	0.001	0.009	0.013	0.016	0.024
1.98	0.000	0.000	0.000	0.000	0.001	0.009	0.013	0.015	0.023
1.99	0.000	0.000	0.000	0.000	0.000	0.008	0.012	0.015	0.022
2.00	0.000	0.000	0.000	0.000	0.000	0.008	0.012	0.014	0.022
2.01	0.000	0.000	0.000	0.000	0.000	0.007	0.011	0.014	0.021
2.02	0.000	0.000	0.000	0.000	0.000	0.007	0.011	0.013	0.021
2.03	0.000	0.000	0.000	0.000	0.000	0.006	0.010	0.013	0.020
2.04	0.000	0.000	0.000	0.000	0.000	0.006	0.010	0.012	0.020
2.05	0.000	0.000	0.000	0.000	0.000	0.006	0.009	0.012	0.019
2.06	0.000	0.000	0.000	0.000	0.000	0.005	0.009	0.011	0.019
2.07	0.000	0.000	0.000	0.000	0.000	0.005	0.009	0.011	0.018
2.08	0.000	0.000	0.000	0.000	0.000	0.004	0.008	0.010	0.018
2.09	0.000	0.000	0.000	0.000	0.000	0.004	0.008	0.010	0.018
2.10	0.000	0.000	0.000	0.000	0.000	0.004	0.007	0.010	0.017
2.11	0.000	0.000	0.000	0.000	0.000	0.004	0.007	0.009	0.017
2.12	0.000	0.000	0.000	0.000	0.000	0.003	0.007	0.009	0.016
2.13	0.000	0.000	0.000	0.000	0.000	0.003	0.006	0.008	0.016
									(Sheet 6 of 9)

Table A3 (Continued)									
	Sample Size								
Q_U or Q_L	2	3	4	5	6	8	10	12	100
2.14	0.000	0.000	0.000	0.000	0.000	0.003	0.006	0.008	0.015
2.15	0.000	0.000	0.000	0.000	0.000	0.003	0.006	0.008	0.015
2.16	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.007	0.015
2.17	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.007	0.014
2.18	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.007	0.014
2.19	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.007	0.013
2.20	0.000	0.000	0.000	0.000	0.000	0.002	0.004	0.006	0.013
2.21	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.006	0.013
2.22	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.006	0.012
2.23	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.005	0.012
2.24	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.005	0.012
2.25	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.005	0.011
2.26	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.005	0.011
2.27	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.004	0.011
2.28	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.004	0.011
2.29	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.004	0.010
2.30	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.004	0.010
2.31	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.004	0.010
2.32	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.003	0.009
2.33	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.003	0.009
2.34	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.003	0.009
2.35	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.003	0.009
2.36	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.003	0.008
2.37	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.008
2.38	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.008
2.39	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.008
2.40	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.008
2.41	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.007
2.42	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.007
2.43	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.007
2.44	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.007
2.45	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.007
2.46	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.006
2.47	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.006
2.48	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.006
2.49	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.006

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Table A3 (Continued)									
	Sample Size								
Q_U or Q_L	2	3	4	5	6	8	10	12	100
2.50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.006
2.51	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.005
2.52	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.005
2.53	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.005
2.54	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.005
2.55	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.005
2.56	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.005
2.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.005
2.58	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.004
2.59	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.004
2.60	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.004
2.61	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.004
2.62	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
2.63	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
2.64	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
2.65	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
2.66	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
2.67	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
2.68	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
2.69	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
2.70	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
2.71	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
2.72	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
2.73	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
2.74	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
2.75	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
2.76	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.77	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.78	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.79	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.80	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.81	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.82	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.83	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.84	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.85	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002

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Table A3 (Concluded)

Q_U or Q_L	Sample Size 2	3	4	5	6	8	10	12	100
2.86	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.87	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.88	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.89	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.91	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
2.92	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
2.93	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
2.94	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
2.95	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
2.96	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
2.97	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
2.98	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
2.99	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.01	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.02	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.03	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.04	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.05	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.06	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.07	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.08	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.09	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
3.21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

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Appendix B Using the Beta Distribution to Calculate Fraction Nonconforming

In this report, the quality index (Q) function is used to estimate fractions of nonconforming material when sample data are used to estimate the standard deviation of the material characteristic. The lower and upper quality indices are calculated as follows.

$$Q(lower) = Q_L = \frac{mean - lower\ limit}{standard\ deviation} = \frac{\bar{y} - LL}{s} \tag{B-1}$$

or

$$Q(upper) = Q_U = \frac{upper\ limit - mean}{standard\ deviation} = \frac{UL - \bar{y}}{s} \tag{B-2}$$

After calculating the quality indices for a particular material characteristic and for a particular lot, estimates for fraction nonconforming can be obtained by comparing the indices with reference tables in either the U.S. Military Standard 414 (USDOD 1957), the American Society of Quality Control standard ANSI/ASQC Z1.9 (ASQC 1980), or any other document that has reproduced these tables. In this document, reference Q tables are included in Appendix A. Since obtaining these tables may be tedious and since tabular values are not easily adapted to software applications, this appendix provides guidance on direct calculations of fraction nonconforming.

The simplest method of making direct calculations involves the use of the beta probability distribution defined over the interval $0 \le x \le 1$ (Lieberman and Resnikoff 1955). The shape of this simple form of the beta distribution is a function of two parameters: α and β (Benjamin and Cornell 1970; Harr 1987).

$$f(x) = Cx^{\alpha}(1 - x)^{\beta} \qquad 0 \le x \le 1 \tag{B-3}$$

where α and β are greater than -1 and the normalizing constant C is

$$C = \frac{(\alpha + \beta + 1)!}{\alpha! \ \beta!} \tag{B-4}$$

if α and β are integers and

$$C = \frac{\Gamma(\alpha + \beta + 2)}{\Gamma(\alpha + 1) \ \Gamma(\beta + 1)} \tag{B-5}$$

if α and β are not restricted to assuming integer values.

The expected value of the beta distribution is (Harr 1987)

$$E[x(\beta)] = \frac{\alpha + 1}{\alpha + \beta + 2} \tag{B-6}$$

while variance is

$$V[x(\beta)] = \frac{(\alpha + 1) \ (\beta + 1)}{(\alpha + \beta + 2)^2 \ (\alpha + \beta + 3)} \tag{B-7}$$

For any particular estimate of fraction nonconforming, the shape of the beta distribution is dependent on sample size. The parameters, α and β, for the beta distribution are calculated as

$$\alpha = \beta = \frac{n}{2} - 1 \qquad \textit{for} \qquad n \geq 3 \tag{B-8}$$

$$\alpha = \beta = \frac{1}{4} \qquad \textit{for} \qquad n = 2 \tag{B-9}$$

After calculating a quality index (Q) for a lot of material, Q is transformed into $x(\beta)$. The probability of finding a larger Q is equal to the probability of finding a larger x within the beta distribution. The Q is transformed to $x(\beta)$ by

$$x(\beta) = \frac{1}{2}\left(1 - \frac{Q\sqrt{n}}{n - 1}\right) \tag{B-10}$$

Example. Suppose a lot of portland cement concrete is evaluated with a sample of five compressive strength tests. The lower limit (LL) for strength is

34.5 Mpa (5,000 psi). If the sample mean and sample sample standard deviation are found to be 36.2 Mpa (5,250 psi) and 1.38 Mpa (200 psi), respectively, Q_L is calculated as

$$Q_L = \frac{36.2 - 34.5}{1.38} = 1.23 \qquad \text{(B-11)}$$

If quality index tables were available, as in Appendix A, the fraction nonconforming would be estimated as 0.100 (10.0 percent). If the quality index tables were not available, Q could be transformed to x(β)

$$x = \frac{1}{2}\left(1 - \frac{Q\sqrt{n}}{n-1}\right) = \frac{1}{2}\left(1 - \frac{1.23\sqrt{5}}{5-1}\right) = 0.1562 \qquad \text{(B-12)}$$

The probability of obtaining concrete strengths less than the lower limit (LL) is equal to the probability of finding an x(β) less than 0.1562 within the beta distribution defined by the following α and β.

$$\alpha = \beta = \frac{n}{2} - 1 = \frac{5}{2} - 1 = \frac{3}{2} \qquad \text{(B-13)}$$

This beta probability can be obtained from most commercial spreadsheet software using built-in functions that can be included in user-generated equations. For example, the built-in functions in Microsoft® Excel include BETADIST (x, α, β, A, B), where x is the value at which to evaluate the function; α and β are the beta distribution parameters; and A and B are the lower and upper beta distribution boundaries, respectively. Plugging both the known A and B (0 and 1, respectively) and the calculated *x*, α, and β into the function, BETADIST (0.1562, 1.5, 1.5, 0, 1) produces 0.100 (or 10.0 percent) as the probability of obtaining a value of $x(\beta)$ smaller than 0.1562. This is also the probability of finding a concrete strength test result less than the lower limit of 34.5 Mpa (5,000 psi).

Appendix C
Calculations of Buyer and Seller Risks for the Statistical Acceptance Plan

This appendix describes the calculations used for determining buyer and seller risks during the development of a statistical acceptance plan, as described in Chapter 7. Risks are concerned with consequences "on the average," which can be evaluated using the distributions of sample means. Assuming that the variables used for acceptance testing are continuous and tend to be normally distributed, the standard normal distribution can be used to calculate buyer and seller risks. Even if the distributions for variables deviate from normal, the central limit theorem states that the distribution of sample means should still be approximately normal (Freund and Wilson 1993).

Risk calculations can begin with the standard normal values associated with AQL and UQL. Risks shown in Table 12 will be calculated first. These risks are associated with the specification of asphalt cement content, fine aggregate grading, and field density.

$$z_{AQL} = z_{0.05} = 1.645 \tag{C-1}$$

$$z_{UQL} = z_{0.30} = 0.524 \tag{C-2}$$

Buyer and seller risks, both primary and secondary, can be calculated using the standard normal distribution of means. Risks are concerned with expected results "over the long-run" or "on the average."

$$z = \frac{|\bar{y} - \mu|}{\frac{1}{\sqrt{n}}} \tag{C-3}$$

The standard deviation of means in this equation is shown to be

$$\sigma_{\bar{z}} = \frac{\sigma_z}{\sqrt{n}} = \frac{1}{\sqrt{n}} \tag{C-4}$$

For example, let's calculate the seller and buyer risks when sample size is n=4 for asphalt cement content (i.e. Table 12). The standard normal values associated with the acceptance value (c) and the rejection value (r) are as follows.

$$z_c = z_{0.10} = 1.282 \tag{C-5}$$

$$z_r = z_{0.28} = 0.583 \tag{C-6}$$

Now the seller's primary risk, which is the probability that a lot of quality AQL will be rejected, can be estimated as the probability that a mean z associated with AQL (z_{AQL}) is sampled as a mean z associated with r (z_r).

$$z(\alpha_r) = \frac{z_{AQL} - z_r}{\frac{1}{\sqrt{n}}} = \frac{1.645 - 0.583}{\frac{1}{\sqrt{4}}} = 2.124 \tag{C-7}$$

$$P(Z > 2.124) = 0.017 \tag{C-8}$$

The probability that a lot of quality AQL will be rejected is 0.017. Similar risks can be calculated for other sample sizes by repeating the above calculations with the proper n and the proper z_r.

The buyer's primary risk, which is the probability that a lot of quality UQL will be accepted at full price, can be estimated às the probability that a mean z associated with UQL (z_{UQL}) is sampled as a mean z associated with c (z_c).

$$z(\beta_c) = \frac{z_c - z_{UQL}}{\frac{1}{\sqrt{n}}} = \frac{1.282 - 0.524}{\frac{1}{\sqrt{4}}} = 1.516 \tag{C-9}$$

$$P(Z > 1.516) = 0.065 \tag{C-10}$$

The probability that a lot of quality UQL will be accepted at full price is 0.065. Similar risks can be calculated for other sample sizes by repeating the above calculations with the proper n and the proper z_c.

Now the seller's secondary risk, which is the probability that a lot of quality AQL will be rejected or accepted with reduced payment, can be estimated as the probability that a mean z associated with AQL (z_{AQL}) is sampled as a mean z associated with c (z_c).

$$z(\alpha_c) = \frac{z_{AQL} - z_c}{\frac{1}{\sqrt{n}}} = \frac{1.645 - 1.282}{\frac{1}{\sqrt{4}}} = 0.726 \tag{C-11}$$

$$P(Z > 0.726) = 0.234 \tag{C-12}$$

The probability that a lot of quality AQL will be rejected or accepted with reduced payment is 0.234. Similar risks can be calculated for other sample sizes by repeating the above calculations with the proper n and the proper z_c.

The buyer's secondary risk, which is the probability that a lot of quality UQL will be accepted at full price or accepted with reduced payment, can be estimated as the probability that a mean z associated with UQL (z_{UQL}) is sampled as a mean z associated with c (z_r).

$$z(\beta_r) = \frac{z_r - z_{UQL}}{\frac{1}{\sqrt{n}}} = \frac{0.583 - 0.524}{\frac{1}{\sqrt{4}}} = 0.118 \tag{C-13}$$

$$P(Z > 0.118) = 0.454 \tag{C-14}$$

The probability that a lot of quality UQL will be accepted at full price or accepted at reduced payment is 0.454. Similar risks can be calculated for other sample sizes by repeating the above calculations with the proper n and the proper z_r.

The operating characteristic curve for a sample size equal to four is shown in Figure C1. The primary and secondary risks for both the seller and the buyer are shown on the figure. Curves for the probability of acceptance at full pay are shown for various sample sizes in Figure C2. Curves for the probability of acceptance at the lowest pay (just prior to rejection) are shown for various sample sizes in Figure C3.

Demonstration calculations will now be performed for risks associated with coarse aggregate grading, as shown in Table 13. The standard normal values associated with AQL and UQL must be recalculated.

$$z_{AQL} = z_{0.10} = 1.282 \tag{C-15}$$

$$z_{UQL} = z_{0.40} = 0.253 \tag{C-16}$$

Calculation demonstrations will use a sample size equal to 4, as in the previous demonstrations. The standard normal values associated with the acceptance value (c) and the rejection value (r) are as follows.

$$z_c = z_{0.16} = 0.994 \tag{C-17}$$

$$z_r = z_{0.38} = 0.305 \tag{C-18}$$

Now the seller's primary risk, which is the probability that a lot of quality AQL will be rejected, can be estimated as the probability that a mean z associated with AQL (z_{AQL}) is sampled as a mean z associated with r (z_r).

$$z(\alpha_r) = \frac{z_{AQL} - z_r}{\frac{1}{\sqrt{n}}} = \frac{1.282 - 0.305}{\frac{1}{\sqrt{4}}} = 1.954 \tag{C-19}$$

$$P(Z > 1.954) = 0.026 \tag{C-20}$$

The probability that a lot of quality AQL will be rejected is 0.026. Similar risks can be calculated for other sample sizes by repeating the above calculations with the proper n and the proper z_r.

The buyer's primary risk, which is the probability that a lot of quality UQL will be accepted at full price, can be estimated as the probability that a mean z associated with UQL (z_{UQL}) is sampled as a mean z associated with c (z_c).

$$z(\beta_c) = \frac{z_c - z_{UQL}}{\frac{1}{\sqrt{n}}} = \frac{0.994 - 0.253}{\frac{1}{\sqrt{4}}} = 1.482 \tag{C-21}$$

$$P(Z > 1.482) = 0.069 \tag{C-22}$$

The probability that a lot of quality UQL will be accepted at full price is 0.069. Similar risks can be calculated for other sample sizes by repeating the above calculations with the proper n and the proper z_c.

Now the seller's secondary risk, which is the probability that a lot of quality AQL will be rejected or accepted with reduced payment, can be estimated as

the probability that a mean z associated with AQL (z_{AQL}) is sampled as a mean z associated with c (z_c).

$$z(\alpha_c) = \frac{z_{AQL} - z_c}{\frac{1}{\sqrt{n}}} = \frac{1.282 - 0.994}{\frac{1}{\sqrt{4}}} = 0.576 \tag{C-23}$$

$$P(Z > 0.576) = 0.283 \tag{C-24}$$

The probability that a lot of quality AQL will be rejected or accepted with reduced payment is 0.283. Similar risks can be calculated for other sample sizes by repeating the above calculations with the proper n and the proper z_c.

The buyer's secondary risk, which is the probability that a lot of quality UQL will be accepted at full price or accepted with reduced payment, can be estimated as the probability that a mean z associated with UQL (z_{UQL}) is sampled as a mean z associated with c (z_r).

$$z(\beta_r) = \frac{z_r - z_{UQL}}{\frac{1}{\sqrt{n}}} = \frac{0.305 - 0.253}{\frac{1}{\sqrt{4}}} = 0.104 \tag{C-25}$$

$$P(Z > 0.104) = 0..459 \tag{C-26}$$

The probability that a lot of quality UQL will be accepted at full price or accepted at reduced payment is 0.459. Similar risks can be calculated for other sample sizes by repeating the above calculations with the proper n and the proper z_r.

The operating characteristic curve for a sample size equal to four is shown in Figure C4. The primary and secondary risks for both the seller and the buyer are shown on the figure. Curves for the probability of acceptance at full pay are shown for various sample sizes in Figure C5. Curves for the probability of acceptance at the lowest pay (just prior to rejection) are shown for various sample sizes in Figure C6.

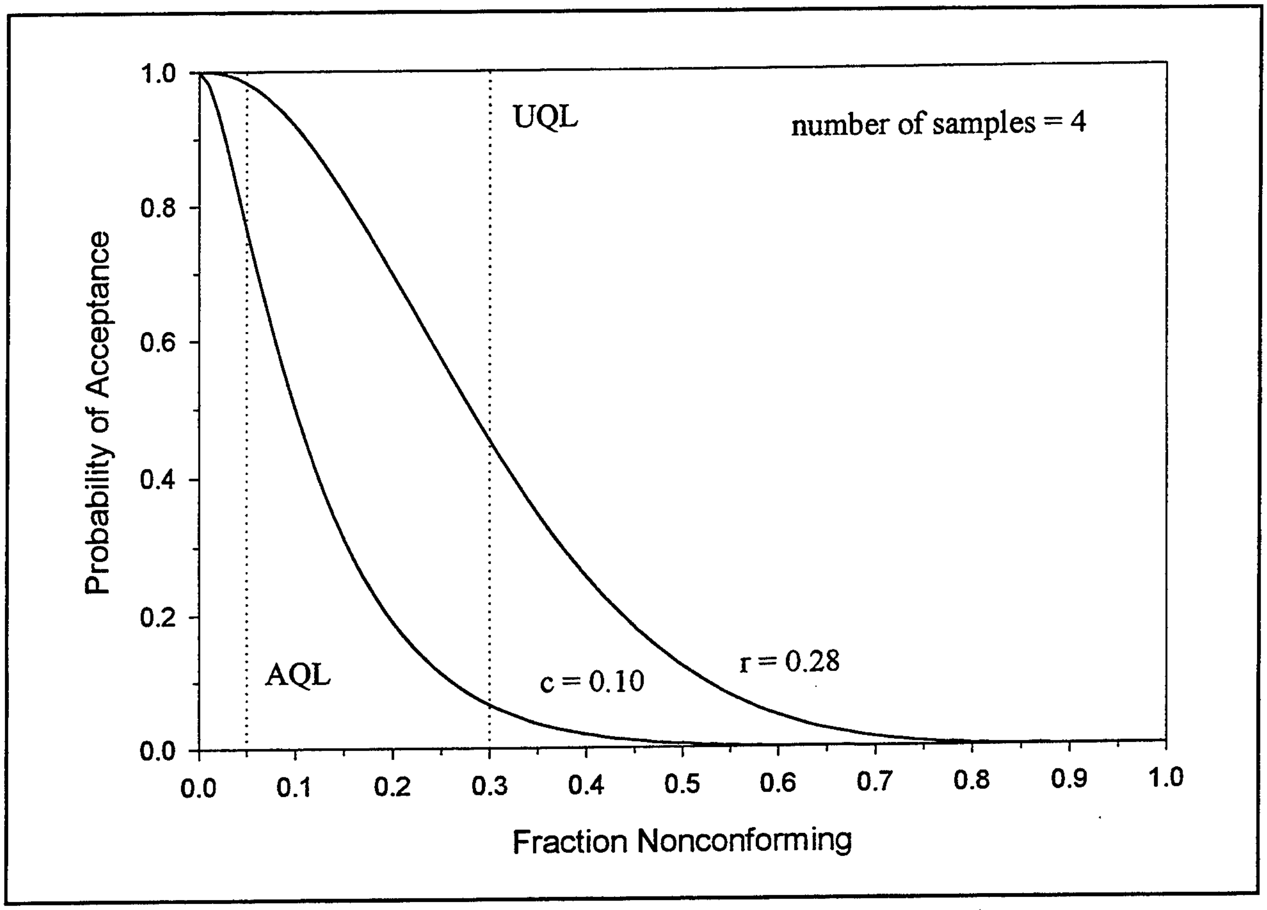

Figure C1. Operating characteristic curve (n = 4) for asphalt cement content, fine aggregate grading, and field density

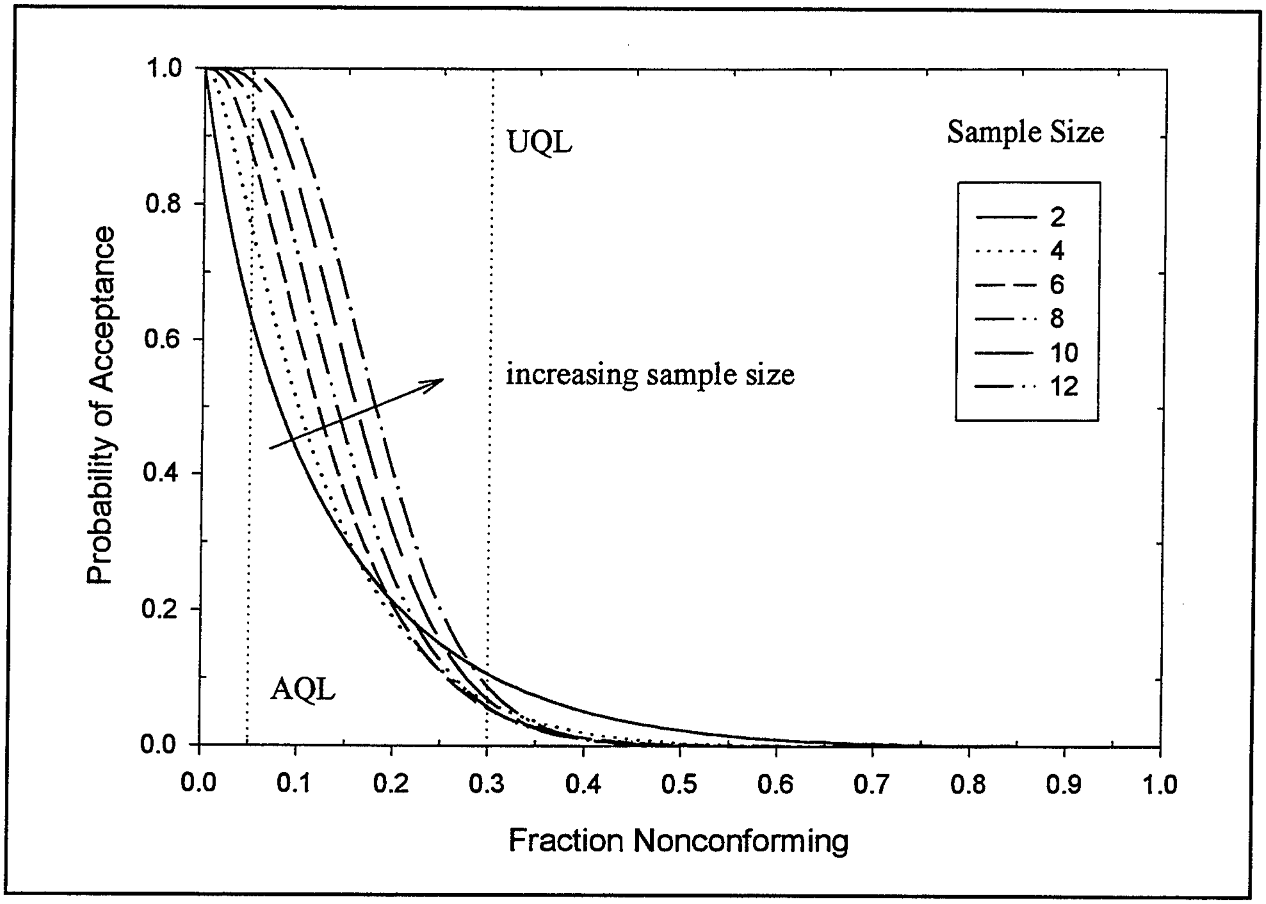

Figure C2. Operating characteristic curves for acceptance of asphalt cement content, fine aggregate grading, and field density at full payment ("c" curves)

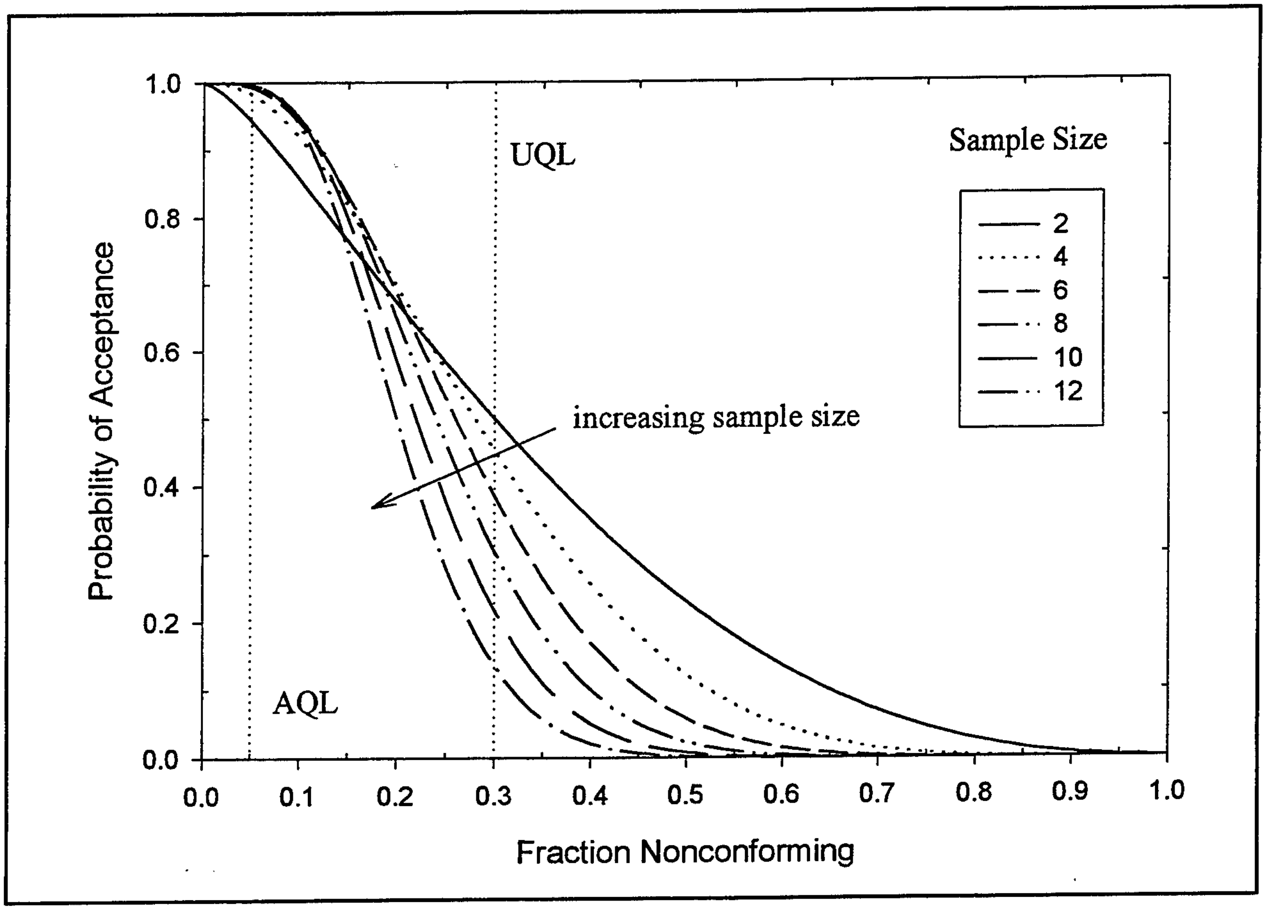

Figure C3. Operating characteristic curves for acceptance of asphalt cement content, fine aggregate grading, and field density at full or adjusted payment ("r" curves)

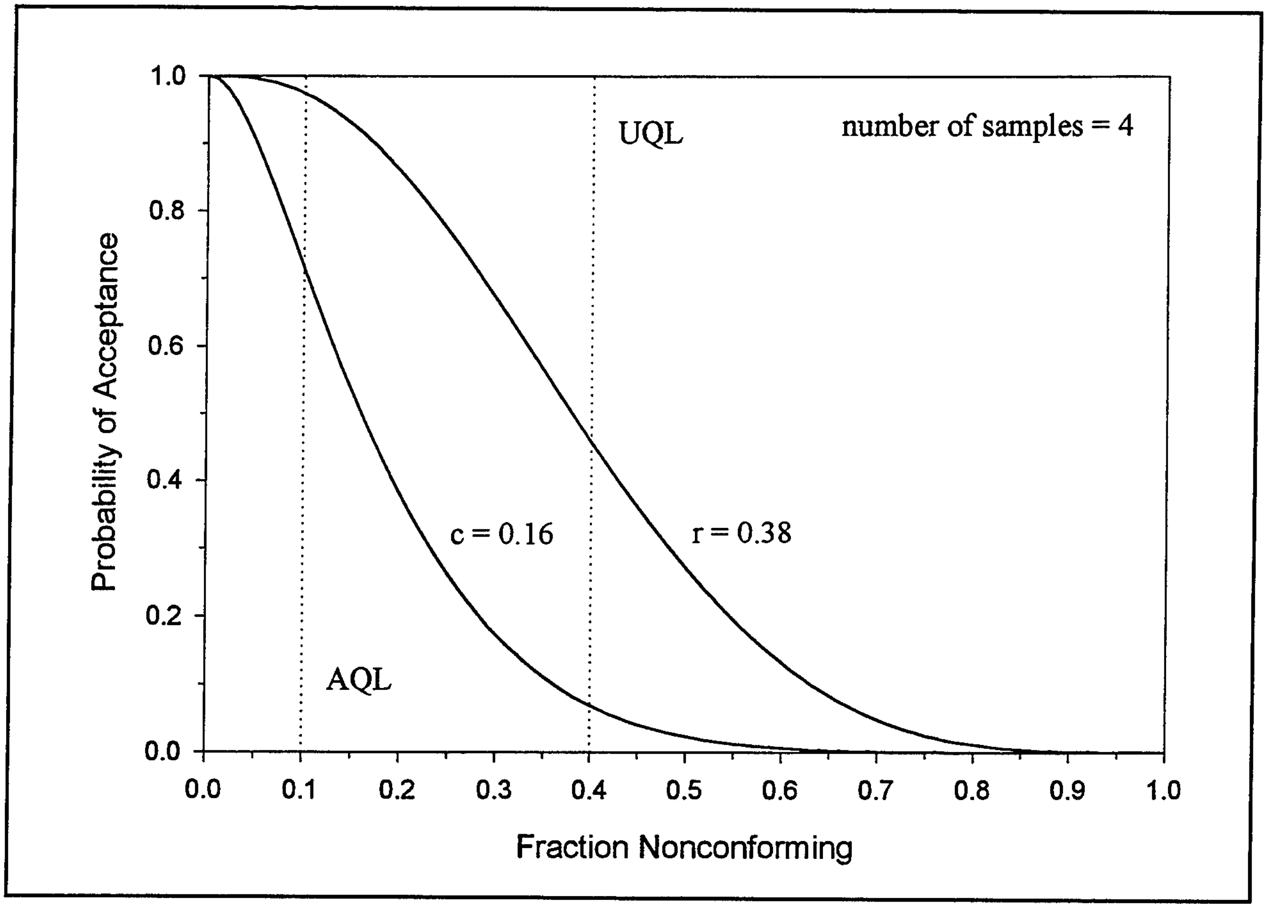

Figure C4. Operating characteristic curve (n = 4) for coarse aggregate grading

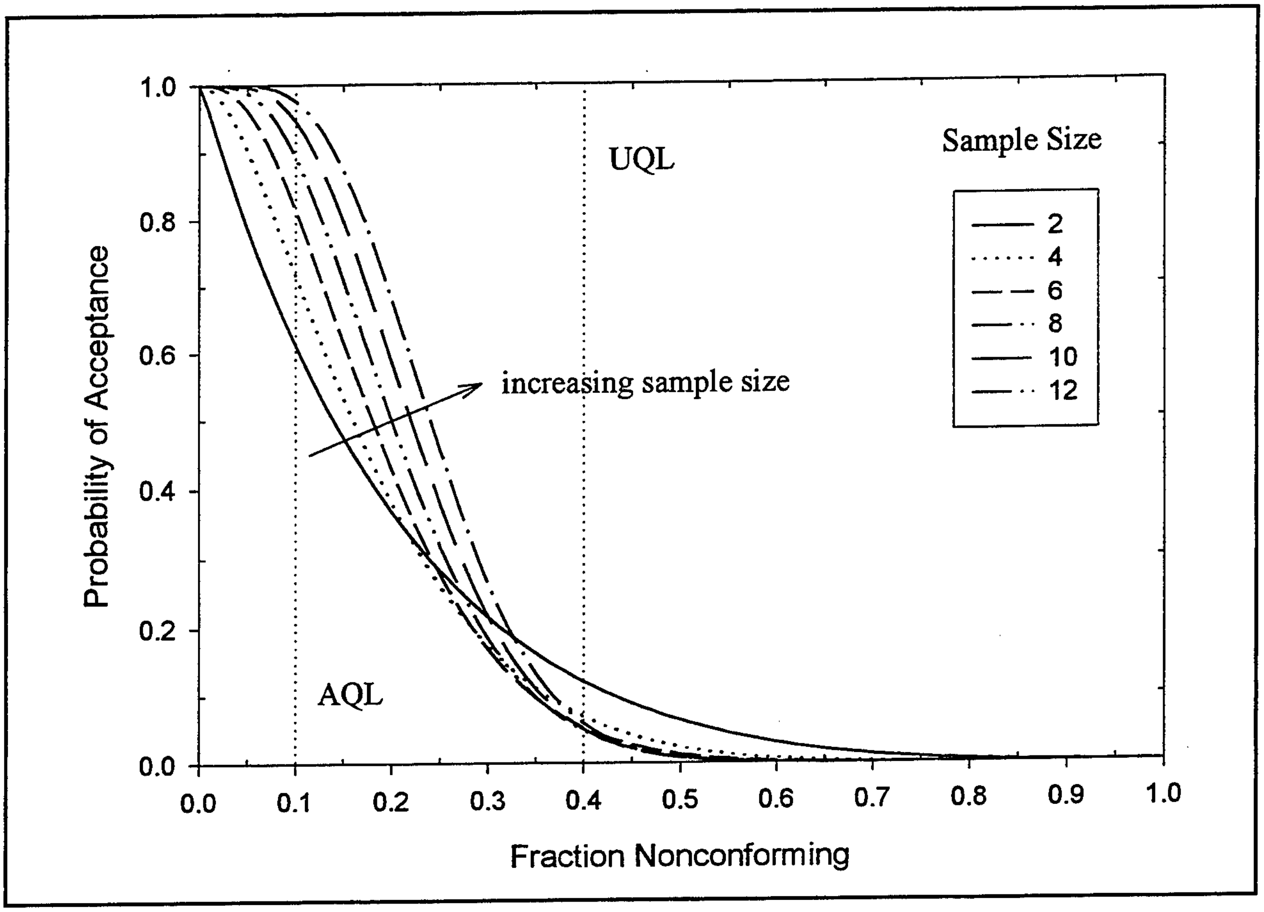

Figure C5. Operating characteristic curves for acceptance of coarse aggregate grading at full payment ("c" curves)

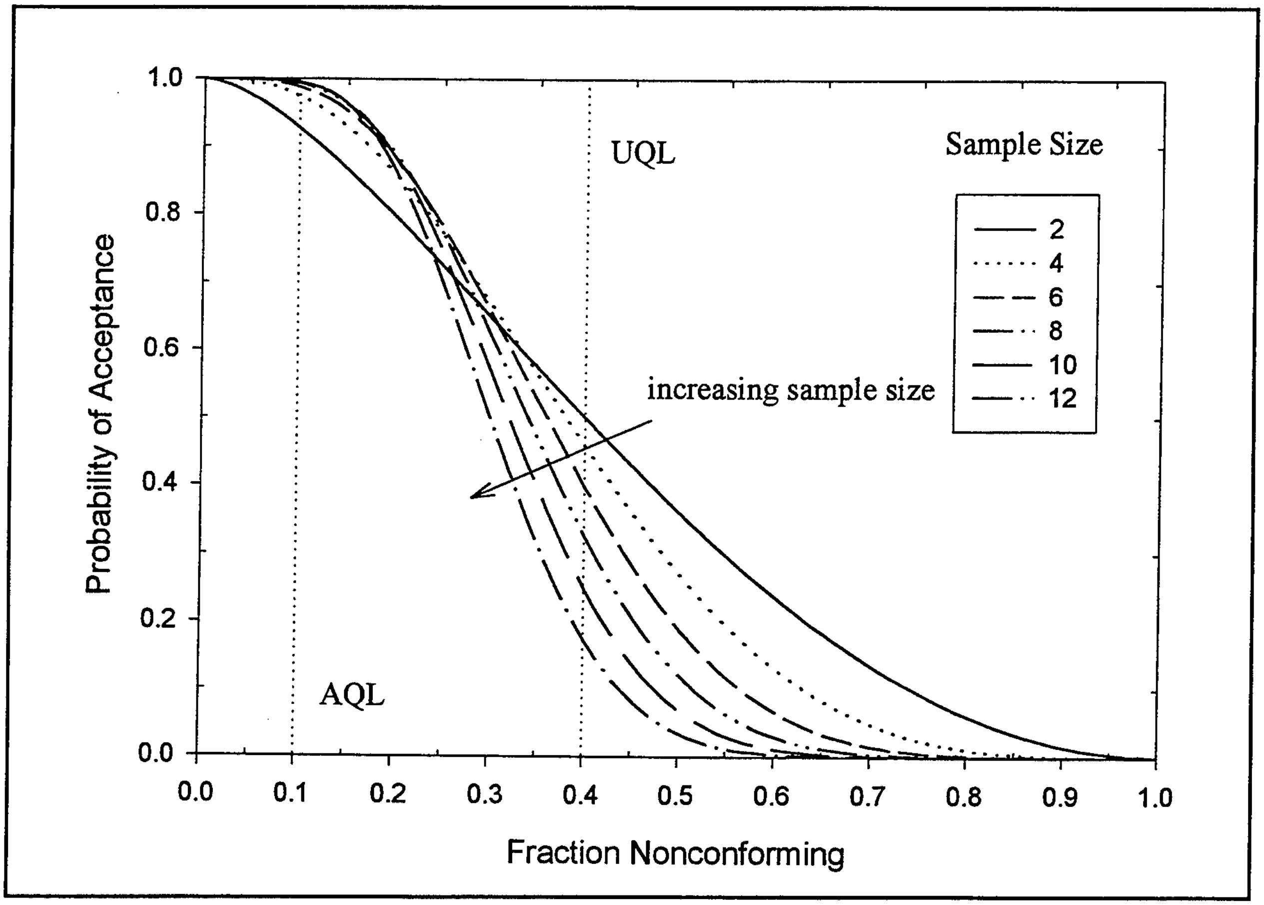

Figure C6. Operating characteristic curves for acceptance of coarse aggregate grading at full or adjusted payment ("r" curves)

Appendix D
Proposed Engineering Technical Letter

STATISTICAL ACCEPTANCE PLAN FOR ASPHALT PAVEMENT CONSTRUCTION

General

Acceptance testing for asphalt concrete materials in CEGS-02556 currently addresses the following material characteristics: asphalt cement content, aggregate gradation, mat density, joint density, smoothness, and grade. Test results for asphalt cement content and aggregate gradation are analyzed in terms of mean absolute deviation from job mix formula; test results for mat and joint densities are analyzed in terms of their mean value; test results for grade and smoothness are analyzed in terms of the percentage of measurements outside of specification limits. Results from each of these acceptance tests can either cause a lot of material to be rejected or can affect contractor payment. The current acceptance criteria were developed for the case of dividing each lot into four sublots. Intermittent construction situations become confusing when the four sublot rule is enforced; sublots from different days of production and from different locations are often combined to form lots.

The following statistical acceptance plan addresses the same material characteristics as the current guide specification. Asphalt cement content, aggregate gradation, mat density, and joint density are analyzed by a "fraction nonconforming" approach, where nonconforming material is that fraction that falls outside of specification limits. Results from each of these acceptance tests can either cause a lot of material to be rejected or can affect contractor payment. Smoothness and grade are still analyzed in terms of the percentage of measurements outside of specification limits, but no pay adjustments are involved. These results can, however, necessitate the correction of deficient areas. Although this statistical acceptance plan recommends that the initial sampling scheme be designed to achieve four sublots per lot, it is flexible in terms of the number of sublots that are actually produced. This statistical acceptance plan, therefore, can handle cases where construction must be stopped and cases where the number of sublots happens to exceed four.

Modifications to CEGS-02556 (June 1991)

Replace Section 3.15, "Percent Payment," with the following.

3.15 PERCENT PAYMENT

3.15.1 Lot Size

****

NOTE: The lot size can be specified on the basis of time (i.e., 4 hours, 1 day, etc.) or amount of production (i.e., 450 metric tons (500 tons), 900 metric tons (1000 tons), etc.). If the lot size is based on the amount of production, it should be selected to be approximately equal to the amount of asphalt mix produced in one day's operation. The lot size should not exceed 1800 metric tons (2000 tons) of asphalt mix. When a lump-sum contract is used (total job does not exceed 900 metric tons (1000 tons)), the lot size becomes the total job; thus the percent payment is applied to the contract price. The following paragraphs will be edited accordingly.

\&Consult CEMP-ET on test method to be used and indicate below.&\

****

A lot will be that quantity of construction that will be evaluated for compliance with specification requirements. A lot will be equal to [[____] \^metric tons^\ \~tons~\] [[____] hour's production], [8 hours production]. In order to define sublot size for the purpose of collecting samples for asphalt content, aggregate gradation, and laboratory density each anticipated lot size shall be divided into four equal-sized sublots. Once the sampling increment (in metric tons of material or hour's production) has been established for a particular lot, it should remain as consistent as possible. However, the final number of sublot samples does not have to be four; it can be more or less, depending on the actual production achieved for the lot.

3.15.2 Sampling

3.15.2.1 Sampling Loose Mix

The quantity of material sampled from a single location for each sublot shall be sufficient to produce two sets of tests for determining laboratory density, asphalt content, and aggregate gradation. The material will be taken from a loaded truck delivering mixture or from another appropriate location in the sublot. All samples will be deliberately selected to be truly random (not haphazard), using commonly recognized methods of assuring randomness, such as employing random number tables or computer programs. Only one set of tests will be performed unless one of the following two situations occurs: (1) production stops after only a single sublot or (2) human or mechanical error invalidates the results of the first set of tests. If either of these situations occurs, a second set of tests shall be performed.

3.15.2.2 Obtaining Cores

For field density determination, one random sample will be taken from the mat, and one random sample will be taken from the longitudinal joint of each sublot. Mat samples, obtained from the interior of the lane, should be selected from material at least 0.3 m (1 ft) from joints. Joint samples should be obtained by centering the core barrel directly over the joint. Each random core sample will weigh at least \^1250 grams.^\ \~1250 grams.~\ The Contractor shall fill all sample holes with hot mix and compact.

The number of sublots for field density determination will be determined by the number of sublots achieved for laboratory density. An exception would be if only a single sublot is produced. In this case two random samples will be taken from both the mat and the joint.

3.15.2.3 Grade

****

NOTE: For heavy-duty roads, replace the third sentence with the one in brackets.

****

Grade conformance tests will be conducted by the Government, on the lot as a whole. The finished surface of the pavement will be tested for conformance with specified plan-grade requirements. The finished grade of each pavements area will be determined by running lines of levels at intervals of \^8 meters^\ \~25 feet~\ or less longitudinally and transversely to determined the elevation of the completed pavement. [The finished grade of each pavement area will be determined by running lines of level along the centerline and each edge at stations of \^8 meters^\ \~25 feet~\ or less.]

3.15.2.4 Smoothness

Surface smoothness determinations will be made on the lot as a whole. After the completion of final rolling of a lot, the compacted surface will be tested by the Contracting Officer with a \^3.66 meter (12 foot)^\ \~12 foot~\ straightedge. Measurements will be made perpendicular to and across all joints at equal distances along the joint not to exceed \^8 meters.^\ \~25 feet.~\

3.15.3 Testing and Reporting

3.15.3.1 Asphalt Content

Asphalt content will be determined in accordance with \-ASTM D 2172-\, Method A or B. All asphalt content tests will be completed and reported within 24 hours after completion of the construction of each lot.

3.15.3.2 Aggregate Gradation

Gradation of the aggregate will be determined from the recovered aggregate according to \-ASTM C 136-\ and \-ASTM C 117-\. All tests for aggregate

gradation will be completed and reported within 24 hours after completion of the construction of each lot.

3.15.3.3 Laboratory Density

A single test for determining laboratory density for a sublot will consist of three compacted specimens. In the event that a single sublot is produced, two tests will be performed, producing six compacted specimens. Laboratory specimens will be prepared from asphalt mixture which has not been reheated in the laboratory. Specimens will be compacted in accordance with \&[ ]&\ within 2 hours of the time the mixture was loaded into trucks at the asphalt plant and before the temperature of the specimen has dropped to \^120 degrees C (250 degrees F).^\ \~250 degrees F.~\ Insulated containers shall be used as necessary to maintain the temperature. The laboratory density for each lot will be determined in accordance with \&[____]&\. In addition to determining laboratory density, Marshall stability, flow, total voids and voids filled will be determined for all specimens.

3.15.3.3 Field Density

After air drying to a constant weight, random core samples obtained from the mat (interior of the lane) and from the joints will be used for field density determination according to \&[______]&\. The average mat density will be expressed as a percentage of the laboratory density for the lot from which it was obtained. The average longitudinal joint density will also be expressed as a percentage of laboratory density, as described below. All density results on a lot will be completed and reported within 24 hours after the construction of that lot.

Calculations for joint samples are related to the type of longitudinal joint; three different scenarios can occur. In one case, two adjacent lanes are placed as part of the same lot of material. The joint density cores will then be compared to the average laboratory density calculated for the lot. In a second case, two adjacent lanes can be placed as part of different lots within the same project. The joint density cores will then be compared to the overall average of the laboratory densities for the two lots of material placed in the adjacent lanes. In a third case, a paving lane can be placed against a bituminous pavement constructed under a different project. In this case, the joint will not be considered as part of the acceptance plan.

3.15.3.4 Grade

Grade measurements are compared to the tolerances specified in paragraph, "Plan Grade Requirement." The Contracting Officer will inform the Contractor in writing of the results for grade-conformance tests within 5 working days after the completion of placement of a particular lot.

3.15.3.5 Surface Smoothness

Straightedge measurements are compared to the tolerance specified in paragraph, "Surface Smoothness Requirement." Location and deviation from straightedge for all measurements will be recorded.

3.15.4 Specification Limits and Calculating Fraction Nonconforming

Fraction noncoforming (FN) refers to the fraction of material that falls outside of specification limits. FN, which requires that material characteristics be handled as continuous variables, will be calculated for asphalt content, percent passing each sieve size, mat density, and joint density. Grade and smoothness measurements will be handled differently, as will be discussed later. The specification limits used for FN calculations are shown in Table 1 for each applicable material characteristic. FN is calculated with the help of quality index (Q) statistics, which first require the calculation of sample means (averages) and standard deviations.

$$sample\ mean = \bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}$$

where

y_i = each measurement
n = number of measurements

Table 1
Specification Limits

Material Characteristic	Lower Limit[1]	Upper Limit[1]
Sieve Size (mea. units = percent passing)		
19.0 mm	JMF - 6.0	JMF + 6.0
12.5 mm	JMF - 7.5	JMF + 7.5
9.5 mm	JMF - 9.0	JMF + 9.0
4.75 mm	JMF - 9.0	JMF + 9.0
2.36 mm	JMF - 9.0	JMF + 9.0
1.18 mm	JMF - 9.0	JMF + 9.0
0.60 mm	JMF - 9.0	JMF + 9.0
0.30 mm	JMF - 7.5	JMF + 7.5
0.15 mm	JMF - 6.0	JMF + 6.0
0.075 mm	JMF - 4.5	JMF + 4.5
Asphalt Content (%)	JMF - 0.6	JMF + 0.6
Relative Mat Density (%)	95	102
Relative Joint Density (%)	93.5	N/A[2]

[1] JMF = job-mix formula target value
[2] no upper limit

Sample standard deviation is the square root of sample variance. Sample variance and standard deviation are calculated as shown below.

$$\textit{sample variance} = s^2 = \frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n-1}$$

$$\textit{standard deviation} = s = \sqrt{s^2}$$

Having established properties for the sampled material characteristic, the upper and lower quality index (Q) statistics can be calculated using the established specification limits.

$$Q(upper) = Q_U = \frac{UL - \bar{y}}{s}$$

$$Q(lower) = Q_L = \frac{\bar{y} - LL}{s}$$

The fraction nonconforming to the upper and lower limits can be obtained using Q_U and Q_L, respectively. Each Q is compared to Table A1, using the appropriate sample size. The total fraction nonconforming (FN) is then calculated as the sum of FN associated with each of Q_U and Q_L.

3.15.5 Acceptance

3.15.5.1 Acceptance Criteria for Fraction Nonconforming

FN values calculated for asphalt content, mat density, joint density, and fine aggregate gradation are compared to the acceptance and rejection criteria shown in Table 2. Fine aggregates are considered to include those particles passing the 4.76-mm (No. 4) sieve. FN values calculated for coarse aggregate gradation are compared to the acceptance and rejection criteria shown in Table 3.

Table 2
Acceptance Criteria for Asphalt Content,
Mat Density, Joint Density, and Fine Aggregate Gradation

Number of Sublots (n)	Acceptance Value for FN, c	Rejection Value for FN, r
2	0.08	0.30
3	0.09	0.29
4	0.10	0.28
5	0.11	0.27
6	0.12	0.26
7	0.13	0.25
8	0.14	0.24
9	0.15	0.23
10	0.16	0.22
11	0.17	0.21
12	0.18	0.20

Table 3
Acceptance Criteria for Coarse Aggregate Gradation

Number of Sublots (n)	Acceptance Value for FN, c	Rejection Value for FN, r
2	0.14	0.40
3	0.15	0.39
4	0.16	0.38
5	0.17	0.37
6	0.18	0.36
7	0.19	0.35
8	0.20	0.34
9	0.21	0.33
10	0.22	0.32
11	0.23	0.31
12	0.24	0.30

Coarse aggregates are considered to include those particles retained on the 4.76-mm (No. 4) sieve and larger. For each material characteristic, the following rules apply when comparing FN values to those in Tables 2 and 3.

a. If $FN \le c$, the lot is accepted at full price with respect to the particular material characteristic.

b. If $FN > r$, the lot is rejected due to the poor quality of the particular material characteristic.

c. IF $c < FN \le r$, the lot is accepted at reduced price due to the poor quality of the particular material characteristic. The corresponding pay factor for the particular material characteristic is calculated as shown below.

$$PF = 1 - r + \frac{r(r - FN)}{r - c}$$

3.15.5.2 Lot Acceptance Based on Fraction Nonconforming

There are 13 material characteristics that can affect payment (10 sieve sizes, asphalt content, mat density and joint density). If all the characteristics warrant full payment, the lot is payed for at full price. If any of the characteristics warrant rejection, the lot is rejected. The one exception is if joint density is the only material characteristic that warrants rejection. In this case, the Contracting Officer has the option of requiring removal and replacement in the area of the joint, rather than rejecting the entire lot. This conditional statement is intended to avoid excessive removal of material in cases where the joint length is small relative to the entire area of the lot. If one or more characteristics warrant a reduction in payment, the lowest computed percent payment shall be applied to the lot. The percent payment for the lot is then applied to the bid price for the quantity of bituminous mixture placed. If joint density is one of the characteristics with a payment reduction, its pay factor must first be adjusted for joint length, in order to compare it with the other material pay factors. Similar to the conditional statement for rejection, this adjustment avoids excessive penalization in cases where the joint length is relatively short. The adjusted PF for joint is calculated as shown below.

$$PF(adjusted) = 1 - \frac{(1 - PF)A_j}{A_t}$$

where

A_j = area of joint = 3m x L_j (not to exceed A_t)
L_j = length of longitudinal construction joint
A_t = total area of material placed for the lot

3.15.5.3 Additional Sampling and Testing

Resampling of a lot of pavement for mat and/or joint density is permitted if the Contractor makes a request in writing within 48 hours of receiving written test results from the Engineer. The cost for resampling and retesting is assumed by the Contractor. Resampling follows similar procedures as the original sampling and testing. Only a single resampling effort is permitted for each lot. The results from resampling are combined with the original sample to calculate a redefined fraction nonconforming, FN. The redefined FN is used to determine acceptability and to calculate payment for the resampled lot. A potential outlier can be tested in accordance with ASTM E 178 (1995c), using a significance level of 5 percent.

The Contracting Officer reserves the right to direct a single resampling and retesting effort for mat and/or joint density for each lot. The rules stated above apply.

3.15.5.4 Lot Acceptance for Grade

When more than 15 percent of all grade measurements made within a lot are outside the specified tolerances, the Contractor must remove deficient areas and replace with new material. Deficient areas and method of rectification will be established by the Contracting Officer. In addition, areas where the grade exceeds the plan-grade tolerances by more than 50 percent must be removed and replaced with fresh paving mixture. Sufficient material shall be removed to allow at least \^25 mm^\ \~1 inch~\ of asphalt concrete to be placed. Skin patching for correcting low areas or planing or milling for correcting high areas shall not be permitted on the wearing course. Rectification will be performed at no additional cost to the Government.

3.15.5.5 Lot Acceptance for Smoothness

When more than 15 percent of all measurements along the joints or along the mat within a lot exceed the specified tolerance, the Contractor must remove deficient areas and replace with new material. Deficient areas and method of rectification will be established by the Contracting Officer. Any joint or mat area surface deviation that exceeds the surface-smoothness tolerances by more than 50 percent shall be corrected to meet the specification requirements. The Contractor shall remove the deficient area and replace with fresh paving mixture. Sufficient material shall be removed to allow at least \^25 mm^\ \~1 inch~\ of asphalt concrete to be placed. Skin patching for correcting low areas or planing or milling for correcting high areas shall not be permitted. Rectification will be performed at no additional cost to the Government.

3.15.6 Example Computations

3.15.6.1 Mean, Variance, and Standard Deviation

The calculation of sample statistics will be demonstrated with asphalt cement content measurements. Assume four sublots were achieved within a lot, as shown in Table 4.

Table 4
Mean and Variance for Asphalt Cement Content

Sample	Asphalt Cement Content, % (y_i)	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
Sublot 1 (i=1)	$y_1 = 6.5$	0.25	0.0625
Sublot 2 (i=2)	$y_2 = 5.9$	-0.35	0.1225
Sublot 3 (i=3)	$y_3 = 6.6$	0.35	0.1225
Sublot 4 (i=4)	$y_4 = 6.0$	-0.25	0.0625
Number of Samples (n) = 4	Sum = 25.0		Sum = 0.37
$\bar{y}$ = sample mean, calculated as shown below			

$$sample\ mean = \bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} = \frac{25.0}{4} = 6.25$$

$$sample\ variance = s^2 = \frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n-1} = \frac{0.37}{4-1} = 0.123$$

$$standard\ deviation = s = \sqrt{s^2} = \sqrt{0.123} = 0.351$$

3.15.6.2 Fraction Nonconforming

The fraction of nonconforming asphalt cement contents will be calculated using the measurements shown in the previous example. The calculation of fraction nonconforming (FN) first requires the calculation of quality index (Q) statistics. Assume that the job mix formula target was 6.0 percent asphalt. The limits can then be determined from Table 1.

$$upper\ limit\ (UL) = JMF + 0.6 = 6.6\ percent$$

$$lower\ limit\ (LL) = JMF - 0.6 = 5.4\ percent$$

Upper and lower quality indices, Q_U and Q_L respectively, are calculated relative to these limits.

$$Q_U = \frac{UL - \bar{y}}{s} = \frac{6.6 - 6.25}{0.351} = 1.00$$

$$Q_L = \frac{\bar{y} - LL}{s} = \frac{6.25 - 5.4}{0.351} = 2.42$$

Fraction nonconforming is now obtained with the help of Table A1, using the calculated Q statistics and the appropriate sample size. The FN relative to the upper limit, which is obtained using Q_U=1.00, is found to be 0.167. The FN relative to the lower limit, which is obtained using Q_U=2.42, is found to be

0.000. The total FN is then calculated as the sum of the upper and lower components; total FN equals 0.167.

3.15.6.3 Acceptance

Continuing with the example of asphalt cement content measurements, the fraction nonconforming (FN) can be compared to specification criteria to determine whether the lot should be accepted at full payment, accepted at reduced payment, or rejected. From Table 2, with consideration for the sample size (n=4), the acceptance value (c) and the rejection value (r) are found to be 0.10 and 0.28, respectively. Since the calculated FN is between c and r, the lot should receive a pay adjustment, due to the level of nonconformance of asphalt cement content. The appropriate pay factor (PF) is calculated as follows.

$$PF = 1 - r + \frac{r(r - FN)}{r - c}$$

$$PF = 1 - 0.28 + \frac{0.28(0.28 - 0.167)}{0.28 - 0.10} = 0.90$$

The pay factor (PF) for asphalt cement content is 0.90. In order to determine the acceptance for the entire lot, the FN for each material characteristic included in the acceptance plan must be considered. Assume the FN and PF for all material characteristics are as shown in Table 5. Since the sample size for each material characteristic within the lot should be the same (n=4), the FN for asphalt content, fine aggregate gradation (No. 8 sieve and smaller), mat density, and joint density would all be compared to the same acceptance and rejection values in Table 2. The FN for coarse aggregate gradation would be compared to the acceptance and rejection values in Table 3 for n=4.

Notice that no material characteristic required that the lot be rejected. The aggregate gradation was controlled well, so no sieve size required an adjustment in payment. Mat density was also accepted at full payment. In addition to asphalt cement content, joint density was the only material characteristic that warranted a pay adjustment. Using the equation demonstrated for asphalt cement content, the PF for joint density was initially calculated as 0.84. However, joint pay factors must be adjusted for the length of joint, relative to total mat area. Assume the length of longitudinal joint was 400 m and that the total mat area was 4800 m^2. The PF adjustment calculation is restated below, followed by the calculation for this example.

$$PF(adjusted) = 1 - \frac{(1 - PF)A_j}{A_t}$$

where

A_j = area of joint = 3m x L_j (not to exceed A_t)
L_j = length of longitudinal construction joint
A_t = total area of material placed for the lot

$$PF(adjusted) = 1 - \frac{(1-0.84)\cdot 1200}{4800} = 0.96$$

The final PF for the lot is defined as the lowest among all material characteristics. In this example, asphalt cement had the lowest PF (= 0.90).

Table 5
Pay Factors for All Material Characteristics

Material Characteristic	Fraction Nonconforming (FN)	Pay Factor
Sieve Size (mea. units = % passing)		
19.0 mm	0.000	1.0
12.5 mm	0.000	1.0
9.5 mm	0.052	1.0
4.75 mm	0.064	1.0
2.36 mm	0.046	1.0
1.18 mm	0.000	1.0
0.60 mm	0.000	1.0
0.30 mm	0.085	1.0
0.15 mm	0.062	1.0
0.075 mm	0.057	1.0
Asphalt Cement Content (%)	0.167	0.90
Relative Mat Density (%)	0.000	1.0
Relative Joint Density (%)	0.200	0.84/0.96[1]
[1] PF was initially calculated as 0.84; it was then adjusted for the length of the joint, relative to mat area [PF(adjusted)=0.96]		

Table A1
Fraction Nonconforming Based on Quality Index Statistics

Note to reader: This table will be a reduced form of Table A3 in this report. Please refer to Table A3.

Appendix E
Acceptance Test Results for an Airfield Paving Project

Table E1
Lot 1 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	1.88	100	91.88	2.098	4.468	2.681	0.000	1.000
9.5 mm	5.90	95	84.90	2.642	5.640	1.173	0.109	1.000
4.75 mm	5.75	95	70.75	2.024	7.287	1.606	0.000	1.000
2.36 mm	3.73	98	54.73	2.204	5.775	2.394	0.000	1.000
1.18 mm	2.33	100	37.33	3.308	3.272	2.169	0.000	1.000
0.60 mm	1.98	100	26.23	2.977	3.267	2.780	0.000	1.000
0.30 mm	1.40	100	17.50	2.258	3.764	2.878	0.000	1.000
0.15 mm	1.63	98	11.63	1.628	4.685	2.688	0.000	1.000
0.075 mm	2.10	90	8.10	1.120	5.895	2.144	0.000	1.000
Asphalt Cement Content (%)	0.20	100	6.25	0.265	2.835	1.701	0.000	1.000
Relative Mat Density (%)	94.23	Reject	94.23	0.779	-0.991	9.978	0.830	Reject
Relative Joint Density (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no joint for lot.

Table E2
Lot 2 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	2.38	100	90.23	3.464	2.230	2.100	0.000	1.000
9.5 mm	3.83	100	82.83	3.799	3.376	1.362	0.046	1.000
4.75 mm	3.15	100	68.15	2.213	5.491	2.644	0.000	1.000
2.36 mm	1.45	100	51.55	2.086	4.579	4.051	0.000	1.000
1.18 mm	2.73	100	36.28	3.448	2.835	2.385	0.000	1.000
0.60 mm	3.43	98	26.73	4.769	2.144	1.630	0.000	1.000
0.30 mm	2.20	100	17.20	2.787	2.942	2.440	0.000	1.000
0.15 mm	0.90	100	10.20	1.227	5.051	4.725	0.000	1.000
0.075 mm	0.95	100	6.95	1.136	4.798	3.126	0.000	1.000
Asphalt Cement Content (%)	0.25	100	5.90	0.216	1.852	3.703	0.000	1.000
Relative Mat Density (%)	93.68	Reject	93.68	1.376	-0.958	6.044	0.819	Reject
Relative Joint Density (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no joint for lot.

Table E3
Lot 3 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	1.33	100	90.93	1.258	6.697	5.227	0.000	1.000
9.5 mm	2.28	100	80.38	2.935	3.535	2.598	0.000	1.000
4.75 mm	1.60	100	66.05	2.456	4.093	3.237	0.000	1.000
2.36 mm	1.20	100	51.60	1.701	5.644	4.938	0.000	1.000
1.18 mm	1.85	100	36.20	2.232	4.347	3.719	0.000	1.000
0.60 mm	1.65	100	26.05	2.249	4.247	3.758	0.000	1.000
0.30 mm	1.45	100	17.10	1.738	4.661	3.971	0.000	1.000
0.15 mm	1.08	98	10.93	1.212	5.713	4.187	0.000	1.000
0.075 mm	1.65	98	7.65	0.998	6.160	2.855	0.000	1.000
Asphalt Cement Content (%)	0.18	100	5.98	0.150	3.167	4.833	0.000	1.000
Relative Mat Density (%)	93.15	Reject	93.15	2.741	-0.674	3.228	0.725	Reject
Relative Joint Density (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[1] mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density
[2] standard deviation
[3] Q_L = lower quality index; Q_U = upper quality index
[4] FN = total fraction nonconforming
N/A - no joint for lot

Table E4
Lot 4 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	2.28	100	90.93	2.681	3.142	2.452	0.000	1.000
9.5 mm	2.08	100	80.48	2.472	4.238	3.045	0.000	1.000
4.75 mm	2.23	100	65.93	2.678	3.707	3.016	0.000	1.000
2.36 mm	1.68	100	51.48	2.161	4.385	3.945	0.000	1.000
1.18 mm	1.00	100	35.15	1.190	7.267	7.856	0.000	1.000
0.60 mm	0.88	100	24.73	0.826	9.956	11.83	0.000	1.000
0.30 mm	0.45	100	16.05	0.420	16.77	18.91	0.000	1.000
0.15 mm	0.45	100	10.15	0.597	10.30	9.795	0.000	1.000
0.075 mm	0.95	100	6.95	0.545	10.01	6.518	0.000	1.000
Asphalt Cement Content (%)	0.18	100	6.08	0.222	2.593	2.819	0.000	1.000
Relative Mat Density (%)	96.64	90.3	96.64	0.900	1.830	5.972	0.000	1.000
Relative Joint Density (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no joint for lot.

Table E5
Lot 5 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.00
12.5 mm	1.58	100	89.73	2.134	3.385	3.643	0.000	1.00
9.5 mm	2.18	100	80.08	2.959	3.405	2.678	0.000	1.00
4.75 mm	2.25	100	65.85	2.710	3.635	3.008	0.000	1.00
2.36 mm	1.58	100	51.83	1.789	5.554	4.621	0.000	1.00
1.18 mm	1.15	100	35.80	1.383	6.723	6.290	0.000	1.00
0.60 mm	1.20	100	25.60	1.445	6.300	6.161	0.000	1.00
0.30 mm	0.93	100	16.33	1.330	5.507	5.770	0.000	1.00
0.15 mm	1.05	98	9.75	1.370	4.197	4.562	0.000	1.00
0.075 mm	0.88	100	6.43	1.124	4.383	3.627	0.000	1.00
Asphalt Cement Content (%)	0.25	100	5.95	0.289	1.559	2.598	0.000	1.00
Relative Mat Density (%)	96.26	83.3	96.26	0.626	2.020	9.159	0.000	1.00
Relative Joint Density (%)	96.15	99.8	96.15	0.981	2.697	N/A	0.000	1.00

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E6
Lot 6 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	2.13	100	91.13	2.363	3.650	2.698	0.000	1.000
9.5 mm	4.85	98	83.85	1.139	12.16	3.644	0.000	1.000
4.75 mm	4.45	98	69.00	3.477	3.739	1.438	0.021	1.000
2.36 mm	4.45	95	52.05	5.249	1.915	1.515	0.000	1.000
1.18 mm	3.08	98	34.58	4.768	1.694	2.082	0.000	1.000
0.60 mm	2.38	100	24.13	4.148	1.838	2.501	0.000	1.000
0.30 mm	1.58	100	15.48	2.557	2.533	3.335	0.000	1.000
0.15 mm	1.20	98	9.50	1.560	3.526	4.167	0.000	1.000
0.075 mm	0.73	100	6.23	1.115	4.239	3.835	0.000	1.000
Asphalt Cement Content (%)	0.23	100	6.18	0.330	2.043	1.589	0.000	1.000
Relative Mat Density (%)	96.04	75	96.04	0.800	1.312	7.488	0.063	1.000
Relative Joint Density (%)	96.69	100	96.69	1.011	3.154	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E7
Lot 7 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	1.75	100	91.75	0.843	10.98	6.824	0.000	1.000
9.5 mm	6.20	90	85.20	1.699	8.946	1.648	0.000	1.000
4.75 mm	6.98	90	71.98	2.380	6.713	0.851	0.216	0.903
2.36 mm	4.83	95	55.83	1.544	8.957	2.705	0.000	1.000
1.18 mm	1.00	100	36.50	1.111	9.005	7.204	0.000	1.000
0.60 mm	1.33	100	24.38	1.187	6.634	8.529	0.000	1.000
0.30 mm	1.73	100	14.78	0.954	6.057	9.675	0.000	1.000
0.15 mm	1.53	98	8.48	1.231	3.635	6.112	0.000	1.000
0.075 mm	0.93	100	5.33	0.946	4.041	5.468	0.000	1.000
Asphalt Cement Content (%)	0.18	100	6.28	0.096	8.095	4.439	0.000	1.000
Relative Mat Density (%)	96.85	96.3	96.85	0.859	2.149	5.996	0.000	1.000
Relative Joint Density (%)	94.90	85.7	94.90	0.374	3.731	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E8
Lot 8 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	1.25	100	90.05	1.725	4.376	4.318	0.000	1.000
9.5 mm	2.08	100	81.03	2.559	4.308	2.726	0.000	1.000
4.75 mm	1.18	100	65.68	1.642	5.893	5.070	0.000	1.000
2.36 mm	2.00	100	49.00	1.519	4.609	7.243	0.000	1.000
1.18 mm	3.40	98	32.10	2.273	2.464	5.455	0.000	1.000
0.60 mm	3.45	98	22.05	1.923	2.887	6.475	0.000	1.000
0.30 mm	2.25	100	14.25	1.605	3.271	6.074	0.000	1.000
0.15 mm	1.35	98	9.00	1.553	3.219	4.506	0.000	1.000
0.075 mm	1.00	100	5.85	1.377	3.159	3.376	0.000	1.000
Asphalt Cement Content (%)	0.13	100	6.03	0.171	3.074	3.952	0.000	1.000
Relative Mat Density (%)	95.11	Reject	95.11	1.360	0.077	5.074	0.474	Reject
Relative Joint Density (%)	95.32	94.1	95.32	1.027	1.771	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E9
Lot 9 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	3.03	10	90.63	3.783	2.148	1.817	0.000	1.000
9.5 mm	4.63	98	82.13	4.233	2.865	1.388	0.037	1.000
4.75 mm	3.85	10	67.55	3.582	3.225	1.801	0.000	1.000
2.36 mm	2.70	100	51.80	3.224	3.040	2.544	0.000	1.000
1.18 mm	2.53	100	35.33	3.083	2.863	2.976	0.000	1.000
0.60 mm	2.18	100	24.88	2.656	3.153	3.623	0.000	1.000
0.30 mm	1.85	100	16.25	2.283	3.176	3.395	0.000	1.000
0.15 mm	1.48	98	10.23	1.855	3.355	3.113	0.000	1.000
0.075 mm	1.43	98	6.88	1.533	3.507	2.365	0.000	1.000
Asphalt Cement Content (%)	0.13	100	6.18	0.126	5.364	4.172	0.000	1.000
Relative Mat Density (%)	96.18	80.6	96.18	1.209	0.980	4.812	0.173	0.886
Relative Joint Density (%)	95.19	92.2	95.19	1.002	1.688	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E10
Lot 10 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	2.48	100	92.48	1.533	6.508	3.279	0.000	1.000
9.5 mm	6.75	90	85.75	2.114	7.449	1.064	0.145	1.000
4.75 mm	6.03	95	71.03	1.554	9.667	1.914	0.000	1.000
2.36 mm	4.48	95	55.48	0.608	22.18	7.447	0.000	1.000
1.18 mm	1.60	100	37.10	1.017	10.43	7.280	0.000	1.000
0.60 mm	1.00	100	25.55	1.363	6.642	6.568	0.000	1.000
0.30 mm	1.03	100	16.03	1.452	4.837	5.491	0.000	1.000
0.15 mm	0.98	100	9.63	1.352	4.159	4.714	0.000	1.000
0.075 mm	0.78	100	6.13	1.115	4.149	3.925	0.000	1.000
Asphalt Cement Content (%)	0.33	98	6.33	0.310	2.665	1.211	0.096	1.000
Relative Mat Density (%)	95.61	Reject	95.61	1.010	0.602	6.313	0.300	Reject
Relative Joint Density (%)	95.24	92.2	95.24	0.820	2.127	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E11 Lot 11 (4 sublots)								
	Current CEGS 02556		**Modified CEGS 02556**					
Material Characteristic	**MAD or Mean[1]**	**% Pay**	**Mean**	**Std. Dev.[2]**	**Q_L[3]**	**Q_U[3]**	**FN[4]**	**Pay Factor**
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	2.40	100	92.40	0.483	20.49	10.56	0.000	1.000
9.5 mm	4.20	98	83.20	1.483	8.899	3.236	0.000	1.000
4.75 mm	3.40	100	68.40	1.233	10.06	4.542	0.000	1.000
2.36 mm	1.45	100	52.00	1.283	7.793	6.234	0.000	1.000
1.18 mm	2.08	100	33.43	1.801	3.846	6.150	0.000	1.000
0.60 mm	2.85	100	22.65	2.024	3.039	5.855	0.000	1.000
0.30 mm	2.68	100	13.83	1.826	2.642	5.571	0.000	1.000
0.15 mm	2.00	98	8.00	1.334	2.998	5.996	0.000	1.000
0.075 mm	0.90	100	5.10	0.891	4.042	6.063	0.000	1.000
Asphalt Cement Content (%)	0.15	100	5.95	0.100	4.500	7.500	0.000	1.000
Relative Mat Density (%)	95.73	Reject	95.73	0.326	2.229	19.24	0.000	1.000
Relative Joint Density (%)	94.35	Reject	94.35	2.034	0.416	N/A	0.361	Reject

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E12
Lot 12 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	1.15	100	90.50	1.881	4.252	3.720	0.000	1.000
9.5 mm	3.43	100	82.43	1.493	8.322	3.734	0.000	1.000
4.75 mm	2.45	100	66.70	2.844	3.763	2.567	0.000	1.000
2.36 mm	2.40	100	50.45	2.852	2.962	3.348	0.000	1.000
1.18 mm	3.03	100	32.53	2.478	2.431	4.832	0.000	1.000
0.60 mm	3.20	98	22.30	2.099	2.763	5.812	0.000	1.000
0.30 mm	2.20	100	14.30	1.798	2.947	5.394	0.000	1.000
0.15 mm	1.40	98	8.90	1.494	3.279	4.751	0.000	1.000
0.075 mm	0.80	100	5.90	1.123	3.920	4.098	0.000	1.000
Asphalt Cement Content (%)	0.23	100	5.88	1.222	1.691	3.721	0.000	1.000
Relative Mat Density (%)	96.08	78.0	96.08	0.360	2.963	16.32	0.000	1.000
Relative Joint Density (%)	94.34	Reject	94.41	0.924	0.986	N/A	0.171	0.889

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E13
Lot 13 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	0.35	100	90.10	0.535	14.19	13.82	0.000	1.000
9.5 mm	3.33	100	82.03	2.526	4.760	2.365	0.000	1.000
4.75 mm	3.10	100	68.10	2.899	4.173	2.035	0.000	1.000
2.36 mm	1.23	100	51.93	1.674	5.929	4.824	0.000	1.000
1.18 mm	1.65	100	33.85	1.399	5.254	7.614	0.000	1.000
0.60 mm	2.38	100	23.13	1.195	5.542	9.515	0.000	1.000
0.30 mm	2.08	100	14.43	1.401	3.873	6.835	0.000	1.000
0.15 mm	1.45	98	8.60	1.458	3.154	5.074	0.000	1.000
0.075 mm	0.95	100	5.65	1.112	3.732	4.361	0.000	1.000
Asphalt Cement Content (%)	0.43	90	5.68	0.189	0.924	5.415	0.192	0.857
Relative Mat Density (%)	95.99	75.0	95.99	0.439	2.255	13.71	0.000	1.000
Relative Joint Density (%)	94.68	80.6	95.17	1.113	1.504	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E14
Lot 14 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	1.18	100	90.63	1.723	4.715	3.990	0.000	1.000
9.5 mm	2.35	100	80.90	2.655	4.106	2.675	0.000	1.000
4.75 mm	1.80	100	66.80	1.278	8.451	5.634	0.000	1.000
2.36 mm	1.15	100	52.10	0.983	10.27	8.035	0.000	1.000
1.18 mm	0.75	100	34.75	0.580	14.22	16.80	0.000	1.000
0.60 mm	1.30	100	24.20	0.600	12.83	17.17	0.000	1.000
0.30 mm	0.93	100	15.58	0.675	9.739	12.48	0.000	1.000
0.15 mm	0.55	100	9.65	0.714	7.912	8.892	0.000	1.000
0.075 mm	0.65	100	6.45	0.661	7.491	6.129	0.000	1.000
Asphalt Cement Content (%)	0.08	100	6.03	0.050	10.50	13.50	0.000	1.000
Relative Mat Density (%)	96.03	75.0	96.03	0.510	2.003	11.64	0.000	1.000
Relative Joint Density (%)	94.74	80.6	94.74	0.361	3.445	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E15
Lot 15 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	2.38	100	89.28	3.010	2.251	2.732	0.000	1.000
9.5 mm	1.38	100	78.88	1.769	5.017	5.158	0.000	1.000
4.75 mm	1.78	100	63.48	2.152	3.474	4.892	0.000	1.000
2.36 mm	2.98	100	48.03	1.173	5.137	10.21	0.000	1.000
1.18 mm	3.20	98	32.30	0.837	6.932	14.58	0.000	1.000
0.60 mm	2.70	100	22.80	0.887	7.103	13.19	0.000	1.000
0.30 mm	1.63	100	14.88	0.900	6.531	10.14	0.000	1.000
0.15 mm	0.80	100	9.45	0.772	7.056	8.480	0.000	1.000
0.075 mm	0.48	100	6.38	0.602	8.097	6.851	0.000	1.000
Asphalt Cement Content (%)	0.23	100	5.88	0.126	2.980	6.556	0.000	1.000
Relative Mat Density (%)	96.37	85.7	96.37	0.740	1.847	7.615	0.000	1.000
Relative Joint Density (%)	96.11	99.6	96.11	0.340	7.666	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E16
Lot 16 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	1.73	100	88.93	1.960	3.278	4.374	0.000	1.000
9.5 mm	1.70	100	80.35	1.466	7.059	5.217	0.000	1.000
4.75 mm	1.58	100	64.43	2.029	4.646	4.227	0.000	1.000
2.36 mm	1.38	100	49.68	1.493	5.141	6.915	0.000	1.000
1.18 mm	2.85	100	32.65	0.443	13.87	26.72	0.000	1.000
0.60 mm	2.80	100	22.70	0.583	10.63	20.24	0.000	1.000
0.30 mm	2.18	100	14.33	0.866	6.152	11.18	0.000	1.000
0.15 mm	1.38	98	8.63	0.846	5.466	8.717	0.000	1.000
0.075 mm	0.55	100	5.70	0.668	6.284	7.182	0.000	1.000
Asphalt Cement Content (%)	0.23	100	6.18	0.263	2.567	1.996	0.000	1.000
Relative Mat Density (%)	96.72	92.2	96.72	0.630	2.745	8.436	0.000	1.000
Relative Joint Density (%)	96.04	99.4	96.04	0.555	4.571	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E17 **Lot 17 (4 sublots)**									
	Current CEGS 02556		**Modified CEGS 02556**						
Material Characteristic	**MAD or Mean[1]**	**% Pay**	**Mean**	**Std. Dev.[2]**	**Q_L[3]**	**Q_U[3]**	**FN[4]**	**Pay Factor**	
Sieve Size (mea. units = % passing)									
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000	
12.5 mm	1.48	100	89.63	1.979	3.606	3.980	0.000	1.000	
9.5 mm	2.98	100	80.83	3.557	3.044	2.017	0.000	1.000	
4.75 mm	3.93	100	65.03	5.011	1.801	1.791	0.000	1.000	
2.36 mm	2.95	100	50.10	4.114	1.969	2.406	0.000	1.000	
1.18 mm	2.20	100	33.50	2.627	2.665	4.188	0.000	1.000	
0.60 mm	2.60	100	23.60	2.594	2.738	4.203	0.000	1.000	
0.30 mm	2.28	100	15.63	2.670	2.481	3.137	0.000	1.000	
0.15 mm	1.90	98	10.15	2.664	2.309	2.196	0.000	1.000	
0.075 mm	1.60	98	7.10	2.223	2.520	1.530	0.000	1.000	
Asphalt Cement Content (%)	0.18	100	6.08	0.250	2.300	2.500	0.000	1.000	
Relative Mat Density (%)	97.03	97.3	97.03	1.782	1.137	2.792	0.121	0.967	
Relative Joint Density (%)	95.72	98.3	95.72	0.719	3.092	N/A	0.000	1.000	

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E18
Lot 18 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	2.65	100	88.45	3.159	1.884	2.865	0.000	1.000
9.5 mm	2.33	100	78.43	2.975	2.832	3.219	0.000	1.000
4.75 mm	3.53	100	62.83	3.667	1.861	3.047	0.000	1.000
2.36 mm	4.28	95	47.43	3.455	1.570	3.640	0.000	1.000
1.18 mm	4.78	95	30.73	1.406	3.006	9.800	0.000	1.000
0.60 mm	4.48	95	21.03	0.881	5.137	15.30	0.000	1.000
0.30 mm	3.10	98	13.40	0.469	9.381	22.60	0.000	1.000
0.15 mm	1.80	98	8.20	0.082	51.44	95.53	0.000	1.000
0.075 mm	0.55	100	5.45	0.173	22.81	29.16	0.000	1.000
Asphalt Cement Content (%)	0.20	100	5.90	0.141	2.828	5.657	0.000	1.000
Relative Mat Density (%)	96.65	92.2	96.65	0.940	1.743	5.670	0.000	1.000
Relative Joint Density (%)	96.26	99.9	96.26	1.727	1.598	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E19
Lot 19 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.95	100	99.05	1.277	3.955	5.444	0.000	1.000
12.5 mm	1.73	100	91.73	0.981	9.403	5.886	0.000	1.000
9.5 mm	3.85	100	82.85	1.396	9.202	3.688	0.000	1.000
4.75 mm	4.05	98	69.05	1.015	12.86	4.877	0.000	1.000
2.36 mm	1.10	100	51.00	1.549	5.809	5.809	0.000	1.000
1.18 mm	1.70	100	33.85	1.912	3.844	5.569	0.000	1.000
0.60 mm	1.33	100	24.63	1.504	5.402	6.565	0.000	1.000
0.30 mm	1.13	100	15.98	1.315	5.304	6.103	0.000	1.000
0.15 mm	1.10	98	9.45	1.323	4.120	4.951	0.000	1.000
0.075 mm	0.90	100	6.50	1.092	4.577	3.662	0.000	1.000
Asphalt Cement Content (%)	0.38	95	5.83	0.359	0.904	2.435	0.199	0.847
Relative Mat Density (%)	98.18	100	99.18	0.740	4.295	5.164	0.000	1.000
Relative Joint Density (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no joint for lot.

Table E20
Lot 20 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.30	100	99.70	0.600	9.500	10.50	0.000	1.000
12.5 mm	3.73	100	91.63	3.896	2.342	1.508	0.000	1.000
9.5 mm	4.13	98	81.88	3.753	3.164	1.632	0.000	1.000
4.75 mm	3.43	100	66.38	3.848	2.696	1.981	0.000	1.000
2.36 mm	1.95	100	50.45	2.899	2.915	3.294	0.000	1.000
1.18 mm	2.15	100	33.35	1.790	3.827	6.230	0.000	1.000
0.60 mm	1.58	100	23.93	1.226	6.057	8.627	0.000	1.000
0.30 mm	0.83	100	15.68	0.750	8.900	11.10	0.000	1.000
0.15 mm	0.48	100	9.53	0.330	16.72	19.60	0.000	1.000
0.075 mm	0.45	100	6.45	0.173	28.58	23.38	0.000	1.000
Asphalt Cement Content (%)	0.25	100	6.05	0.311	1.769	2.091	0.000	1.000
Relative Mat Density (%)	97.51	99.4	97.51	0.640	3.948	7.070	0.000	1.000
Relative Joint Density (%)	97.40	100	97.40	0.432	9.027	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E21
Lot 21 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	2.08	100	90.23	2.472	3.125	3.943	0.000	1.000
9.5 mm	2.55	100	78.40	3.567	2.355	2.691	0.000	1.000
4.75 mm	3.18	100	63.43	3.583	2.072	2.952	0.000	1.000
2.36 mm	3.95	98	48.00	3.428	1.750	3.500	0.000	1.000
1.18 mm	4.05	95	31.45	2.797	1.770	4.666	0.000	1.000
0.60 mm	3.33	98	22.18	2.012	2.820	6.125	0.000	1.000
0.30 mm	2.38	100	14.13	1.443	3.551	6.843	0.000	1.000
0.15 mm	1.70	98	8.30	1.140	3.771	6.753	0.000	1.000
0.075 mm	0.75	100	5.45	0.835	4.732	6.050	0.000	1.000
Asphalt Cement Content (%)	0.35	98	5.75	0.100	2.500	9.500	0.000	1.000
Relative Mat Density (%)	97.85	100	97.85	0.385	7.398	10.77	0.000	1.000
Relative Joint Density (%)	97.55	100	97.55	1.190	3.403	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E22
Lot 22 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	1.28	100	90.23	1.857	4.160	3.917	0.000	1.000
9.5 mm	2.35	100	81.35	1.593	7.126	4.175	0.000	1.000
4.75 mm	1.00	100	64.45	1.190	7.099	8.024	0.000	1.000
2.36 mm	2.45	100	48.55	1.266	5.173	9.043	0.000	1.000
1.18 mm	2.03	100	33.93	1.795	4.136	5.891	0.000	1.000
0.60 mm	1.53	100	25.03	1.852	4.604	5.117	0.000	1.000
0.30 mm	0.78	100	16.58	1.069	7.087	6.947	0.000	1.000
0.15 mm	0.25	100	10.05	0.289	20.96	20.61	0.000	1.000
0.075 mm	0.90	100	6.75	0.719	7.304	5.217	0.000	1.000
Asphalt Cement Content (%)	0.25	100	5.85	0.058	6.062	14.72	0.000	1.000
Relative Mat Density (%)	96.45	87.9	96.45	0.350	4.120	15.83	0.000	1.000
Relative Joint Density (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no joint for lot.

Table E23
Lot 23 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	1.58	100	88.68	2.148	2.874	4.108	0.000	1.000
9.5 mm	3.13	100	81.68	3.703	3.153	1.708	0.000	1.000
4.75 mm	5.20	95	68.50	5.319	2.350	1.034	0.155	1.000
2.36 mm	5.73	90	49.28	6.662	1.092	1.610	0.136	0.944
1.18 mm	5.30	90	32.90	5.355	1.195	2.166	0.102	0.998
0.60 mm	4.25	95	23.25	4.247	1.589	2.649	0.000	1.000
0.30 mm	2.70	100	15.00	2.746	2.185	3.277	0.000	1.000
0.15 mm	1.58	98	9.18	1.746	2.964	3.909	0.000	1.000
0.075 mm	0.80	100	6.20	1.192	3.944	3.608	0.000	1.000
Asphalt Cement Content (%)	0.23	100	6.08	0.330	1.740	1.892	0.000	1.000
Relative Mat Density (%)	98.20	100	98.20	0.563	5.678	6.758	0.000	1.000
Relative Joint Density (%)	95.85	99.1	95.85	0.412	5.700	NA	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E24
Lot 24 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	2.58	100	90.73	3.303	2.490	2.051	0.000	1.000
9.5 mm	4.48	98	82.83	4.334	2.959	1.194	0.102	1.000
4.75 mm	2.90	100	66.75	3.802	2.827	1.907	0.000	1.000
2.36 mm	3.13	98	49.73	3.939	1.961	2.609	0.000	1.000
1.18 mm	3.13	98	33.78	3.811	1.909	2.814	0.000	1.000
0.60 mm	2.43	100	24.73	3.008	2.734	3.249	0.000	1.000
0.30 mm	1.60	100	16.70	2.080	3.702	3.510	0.000	1.000
0.15 mm	1.10	98	10.75	1.396	4.834	3.760	0.000	1.000
0.075 mm	1.63	98	7.63	1.087	5.633	2.644	0.000	1.000
Asphalt Cement Content (%)	0.23	100	5.98	0.287	1.654	2.524	0.000	1.000
Relative Mat Density (%)	98.20	100	98.20	0.420	7.550	9.981	0.000	1.000
Relative Joint Density (%)	96.85	100	96.85	0.412	8.125	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E25
Lot 25 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.40	100	99.60	0.800	7.000	8.000	0.000	1.000
12.5 mm	1.68	100	91.53	1.680	5.372	3.556	0.000	1.000
9.5 mm	5.60	95	84.60	1.631	8.952	2.085	0.000	1.000
4.75 mm	3.78	100	68.78	1.630	7.839	3.206	0.000	1.000
2.36 mm	1.18	100	50.58	1.850	4.635	5.095	0.000	1.000
1.18 mm	2.53	100	33.58	2.111	3.352	5.176	0.000	1.000
0.60 mm	2.70	100	23.70	2.673	2.693	4.040	0.000	1.000
0.30 mm	1.83	100	15.68	2.300	2.902	3.620	0.000	1.000
0.15 mm	1.25	98	10.00	1.655	3.625	3.625	0.000	1.000
0.075 mm	1.25	98	6.95	1.292	4.217	2.747	0.000	1.000
Asphalt Cement Content (%)	0.30	98	6.35	0.265	3.213	1.323	0.059	1.000
Relative Mat Density (%)	97.49	99.4	97.49	0.728	3.425	6.194	0.000	1.000
Relative Joint Density (%)	97.25	100.0	97.25	0.918	4.083	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E26
Lot 26 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.45	100	99.55	0.900	6.167	7.167	0.000	1.000
12.5 mm	1.88	100	89.73	2.416	2.991	3.218	0.000	1.000
9.5 mm	4.13	98	82.28	3.476	3.531	1.647	0.000	1.000
4.75 mm	3.45	100	66.30	3.773	2.730	2.041	0.000	1.000
2.36 mm	3.03	100	47.98	3.087	1.936	3.895	0.000	1.000
1.18 mm	5.20	90	30.30	2.140	1.776	6.635	0.000	1.000
0.60 mm	4.63	95	20.88	1.634	2.678	8.340	0.000	1.000
0.30 mm	2.85	100	13.65	1.156	4.022	8.952	0.000	1.000
0.15 mm	1.43	98	8.58	0.727	6.289	10.21	0.000	1.000
0.075 mm	0.35	100	5.90	0.455	9.679	10.12	0.000	1.000
Asphalt Cement Content (%)	0.23	100	6.08	0.330	1.740	1.892	0.000	1.000
Relative Mat Density (%)	98.26	100	98.26	0.380	8.603	9.891	0.000	1.000
Relative Joint Density (%)	97.95	100	97.95	0.580	7.669	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E27
Lot 27 (4 sublots)

Material Characteristic	Current CEGS 02556: MAD or Mean[1]	Current CEGS 02556: % Pay	Modified CEGS 02556: Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	2.63	100	89.63	3.820	1.865	2.062	0.000	1.000
9.5 mm	3.73	100	82.38	2.800	4.419	2.009	0.000	1.000
4.75 mm	3.78	100	68.78	2.066	6.183	2.529	0.000	1.000
2.36 mm	0.93	100	50.78	1.176	7.463	7.846	0.000	1.000
1.18 mm	3.73	98	31.78	2.516	2.097	5.058	0.000	1.000
0.60 mm	4.00	98	21.50	2.008	2.490	6.473	0.000	1.000
0.30 mm	3.23	98	13.28	1.310	3.264	8.188	0.000	1.000
0.15 mm	2.23	95	7.78	1.103	3.424	7.459	0.000	1.000
0.075 mm	1.03	100	5.28	0.903	4.179	5.785	0.000	1.000
Asphalt Cement Content (%)	0.15	100	6.00	0.183	2.739	3.834	0.000	1.000
Relative Mat Density (%)	98.73	100	98.73	0.567	6.585	5.765	0.000	1.000
Relative Joint Density (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no joint for lot.

Table E28
Lot 28 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.63	100	99.38	1.250	4.300	5.300	0.000	1.000
12.5 mm	5.65	95	84.35	2.234	0.828	5.887	0.224	0.890
9.5 mm	4.13	98	75.73	3.920	1.461	3.132	0.013	1.000
4.75 mm	4.38	98	64.68	5.474	1.585	1.703	0.000	1.000
2.36 mm	4.20	95	46.80	3.335	1.439	3.958	0.200	1.000
1.18 mm	6.05	Reject	29.45	2.094	1.409	7.188	0.030	1.000
0.60 mm	5.15	90	20.35	1.457	2.642	9.711	0.000	1.000
0.30 mm	3.48	98	13.03	0.991	4.061	11.07	0.000	1.000
0.15 mm	2.15	95	7.85	0.827	4.657	9.859	0.000	1.000
0.075 mm	0.60	100	5.40	0.638	6.116	7.997	0.000	1.000
Asphalt Cement Content (%)	0.55	Reject	5.55	0.370	0.135	3.111	0.455	Reject
Relative Mat Density (%)	97.02	97.3	97.02	0.610	3.333	8.213	0.000	1.000
Relative Joint Density (%)	96.78	100.0	96.78	1.087	3.012	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E29
Lot 29 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.78	100	99.23	0.967	5.401	7.003	0.000	1.000
12.5 mm	2.48	100	87.83	2.035	2.616	4.754	0.000	1.000
9.5 mm	2.43	100	78.78	3.128	2.806	2.949	0.000	1.000
4.75 mm	2.50	100	66.60	3.102	3.418	2.386	0.000	1.000
2.36 mm	1.50	100	49.50	1.169	6.415	8.982	0.000	1.000
1.18 mm	2.30	100	33.55	2.381	2.961	4.599	0.000	1.000
0.60 mm	2.20	100	25.25	2.924	2.992	3.163	0.000	1.000
0.30 mm	1.50	100	16.50	2.012	3.728	3.728	0.000	1.000
0.15 mm	0.73	100	9.83	1.069	5.450	5.777	0.000	1.000
0.075 mm	1.03	100	7.03	0.780	7.079	4.452	0.000	1.000
Asphalt Cement Content (%)	0.20	100	6.05	0.238	2.310	2.731	0.000	1.000
Relative Mat Density (%)	97.10	97.8	97.10	0.762	2.752	6.437	0.000	1.000
Relative Joint Density (%)	96.98	100	96.98	1.335	2.603	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E30
Lot 30 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.48	100	99.53	0.950	5.816	6.816	0.000	1.000
12.5 mm	3.20	100	90.25	4.161	1.862	1.742	0.000	1.000
9.5 mm	3.68	100	80.58	3.936	2.687	1.887	0.000	1.000
4.75 mm	4.35	98	67.25	4.483	2.510	1.506	0.000	1.000
2.36 mm	2.85	100	50.45	3.712	2.277	2.573	0.000	1.000
1.18 mm	2.65	100	35.75	3.248	2.848	2.694	0.000	1.000
0.60 mm	3.08	98	28.13	2.988	3.890	2.133	0.000	1.000
0.30 mm	1.80	100	18.00	1.807	4.980	3.320	0.000	1.000
0.15 mm	0.50	100	10.05	0.656	9.226	9.074	0.000	1.000
0.075 mm	1.25	98	7.25	0.520	11.07	6.255	0.000	1.000
Asphalt Cement Content (%)	0.28	98	5.98	0.359	1.322	2.017	0.059	1.000
Relative Mat Density (%)	96.83	94.1	96.83	1.900	0.961	2.719	0.180	0.876
Relative Joint Density (%)	96.20	99.8	96.20	0.938	2.878	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E31
Lot 31 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.65	100	99.35	0.751	7.128	8.860	0.000	1.000
12.5 mm	2.33	100	88.18	2.568	2.210	3.631	0.000	1.000
9.5 mm	3.30	100	79.05	4.238	2.135	2.112	0.000	1.000
4.75 mm	3.73	100	65.88	4.890	2.020	1.662	0.000	1.000
2.36 mm	2.83	100	49.78	3.678	2.114	2.780	0.000	1.000
1.18 mm	2.05	100	35.10	2.594	3.316	3.624	0.000	1.000
0.60 mm	2.38	100	27.63	2.431	4.577	2.828	0.000	1.000
0.30 mm	1.50	100	17.60	1.476	5.825	4.335	0.000	1.000
0.15 mm	0.58	100	9.63	0.806	6.981	7.912	0.000	1.000
0.075 mm	0.93	100	6.93	0.562	9.654	6.361	0.000	1.000
Asphalt Cement Content (%)	0.35	98	6.05	0.532	1.033	1.221	0.249	0.769
Relative Mat Density (%)	96.20	80.6	96.20	1.492	0.801	3.890	0.233	0.793
Relative Joint Density (%)	97.65	100	97.65	1.170	3.546	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E32
Lot 32 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	1.38	100	88.63	1.692	3.620	5.246	0.000	1.000
9.5 mm	3.68	100	81.83	3.251	3.637	1.899	0.000	1.000
4.75 mm	4.58	98	69.58	3.019	4.496	1.466	0.011	1.000
2.36 mm	0.85	100	51.30	1.329	6.997	6.545	0.000	1.000
1.18 mm	1.23	100	36.03	1.486	6.408	5.702	0.000	1.000
0.60 mm	2.75	100	28.25	1.300	9.038	4.808	0.000	1.000
0.30 mm	1.73	100	18.23	0.850	10.85	6.794	0.000	1.000
0.15 mm	0.63	100	9.98	0.732	8.163	8.231	0.000	1.000
0.075 mm	0.98	100	6.98	0.568	9.641	6.207	0.000	1.000
Asphalt Cement Content (%)	0.23	100	6.13	0.263	2.376	2.186	0.000	1.000
Relative Mat Density (%)	96.42	85.7	96.42	1.280	1.106	4.349	0.131	0.951
Relative Joint Density (%)	95.88	99.1	95.88	1.717	1.383	N/A	0.039	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E33 **Lot 33 (3 sublots)**								
	Current CEGS 02556		**Modified CEGS 02556**					
Material Characteristic	**MAD or Mean[1]**	**% Pay**	**Mean**	**Std. Dev.[2]**	**Q_L[3]**	**Q_U[3]**	**FN[4]**	**Pay Factor**
Sieve Size (mea. units = % passing)								
19.0 mm	0.53	100	99.47	0.924	5.918	7.073	0.000	1.000
12.5 mm	4.97	98	91.23	6.658	1.312	0.941	0.197	0.937
9.5 mm	5.77	95	83.83	8.643	1.601	0.482	0.363	0.650
4.75 mm	5.63	95	70.57	9.215	1.581	0.373	0.395	Reject
2.36 mm	4.93	95	49.20	5.895	1.221	1.832	0.000	1.000
1.18 mm	4.63	95	33.73	5.776	1.252	1.864	0.000	1.000
0.60 mm	4.00	98	26.43	5.818	1.707	1.386	0.000	1.000
0.30 mm	2.97	100	16.13	4.461	1.599	1.763	0.000	1.000
0.15 mm	2.33	95	7.80	3.175	1.197	2.583	0.000	1.000
0.075 mm	1.83	98	5.03	2.804	1.260	1.949	0.000	1.000
Asphalt Cement Content (%)	0.30	98	6.00	0.361	1.387	1.941	0.000	1.000
Relative Mat Density (%)	97.75	99.9	97.75	0.344	8.007	12.36	0.000	1.000
Relative Joint Density (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no joint for lot.

Table E34
Lot 34 (4 sublots)

Material Characteristic	Current CEGS 02556: MAD or Mean[1]	Current CEGS 02556: % Pay	Modified CEGS 02556: Mean	Modified CEGS 02556: Std. Dev.[2]	Modified CEGS 02556: Q_L[3]	Modified CEGS 02556: Q_U[3]	Modified CEGS 02556: FN[4]	Modified CEGS 02556: Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	4.43	98	92.18	4.930	1.962	1.080	0.140	1.000
9.5 mm	5.48	95	84.08	5.320	2.646	0.738	0.254	0.838
4.75 mm	3.63	100	65.23	5.392	1.711	1.628	0.000	1.000
2.36 mm	2.95	100	51.70	4.127	2.350	2.011	0.000	1.000
1.18 mm	3.13	98	37.93	3.317	3.444	1.982	0.000	1.000
0.60 mm	4.40	95	29.90	2.578	5.198	1.784	0.000	1.000
0.30 mm	2.75	100	19.25	1.718	5.968	2.766	0.000	1.000
0.15 mm	1.03	100	10.38	1.284	4.964	4.380	0.000	1.000
0.075 mm	1.40	98	7.40	1.042	5.660	2.974	0.000	1.000
Asphalt Cement Content (%)	0.30	98	6.35	0.370	2.299	0.947	0.184	0.869
Relative Mat Density (%)	98.32	100	98.32	0.670	4.243	4.779	0.000	1.000
Relative Joint Density (%)	96.75	100	96.75	0.451	7.207	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E35
Lot 35 (4 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	3.28	100	86.73	1.791	2.358	6.015	0.000	1.000
9.5 mm	4.48	98	77.13	5.598	1.273	1.943	0.076	1.000
4.75 mm	7.23	90	57.78	6.774	0.262	2.395	0.413	Reject
2.36 mm	5.13	90	45.93	6.443	0.609	2.185	0.297	Reject
1.18 mm	3.58	98	34.13	4.953	1.540	2.095	0.000	1.000
0.60 mm	3.35	98	27.00	3.730	2.815	2.011	0.000	1.000
0.30 mm	1.95	100	17.20	2.459	3.335	2.765	0.000	1.000
0.15 mm	1.40	98	8.90	1.612	3.039	4.403	0.000	1.000
0.075 mm	1.13	98	6.28	1.389	3.438	3.042	0.000	1.000
Asphalt Cement Content (%)	0.38	95	5.73	0.450	0.500	2.167	0.333	Reject
Relative Mat Density (%)	98.04	100	98.04	0.762	3.994	5.197	0.000	1.000
Relative Joint Density (%)	97.45	100	97.45	1.085	3.641	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E36
Lot 36 (4 sublots)

Material Characteristic	Current CEGS 02556 MAD or Mean[1]	Current CEGS 02556 % Pay	Modified CEGS 02556 Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.40	100	99.60	0.800	7.000	8.000	0.000	1.000
12.5 mm	2.63	100	92.63	1.466	6.907	3.325	0.000	1.000
9.5 mm	2.10	100	80.35	2.557	4.048	2.992	0.000	1.000
4.75 mm	3.35	100	61.65	2.447	2.309	5.046	0.000	1.000
2.36 mm	2.55	100	48.45	2.199	2.933	5.251	0.000	1.000
1.18 mm	1.43	100	35.98	1.688	5.613	5.051	0.000	1.000
0.60 mm	3.28	98	28.78	1.450	8.466	3.948	0.000	1.000
0.30 mm	2.35	100	18.85	1.147	8.584	4.488	0.000	1.000
0.15 mm	0.58	100	10.03	0.802	7.517	7.454	0.000	1.000
0.075 mm	1.13	98	7.13	0.746	7.545	4.527	0.000	1.000
Asphalt Cement Content (%)	0.28	98	5.98	0.377	1.258	1.921	0.081	1.000
Relative Mat Density (%)	97.49	99.4	97.49	0.440	5.702	10.31	0.000	1.000
Relative Joint Density (%)	97.08	100.0	97.08	0.532	6.726	N/A	0.000	1.000

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no upper limit.

Table E37 Lot 37 (4 sublots)									
Material Characteristic	**Current CEGS 02556**		**Modified CEGS 02556**						
	MAD or Mean[1]	**% Pay**	**Mean**	**Std. Dev.[2]**	**Q_L[3]**	**Q_U[3]**	**FN[4]**	**Pay Factor**	
Sieve Size (mea. units = % passing)									
19.0 mm	0.25	100	99.75	0.500	11.50	12.50	0.000	1.000	
12.5 mm	3.73	100	91.63	4.310	2.117	1.363	0.046	1.000	
9.5 mm	3.50	100	80.35	4.076	2.539	1.877	0.000	1.000	
4.75 mm	2.95	100	62.50	5.044	1.289	2.280	0.070	1.000	
2.36 mm	4.05	95	51.20	5.333	1.725	1.650	0.000	1.000	
1.18 mm	3.35	98	36.90	3.845	2.705	1.976	0.000	1.000	
0.60 mm	3.30	98	28.35	2.774	4.271	2.217	0.000	1.000	
0.30 mm	1.75	100	17.75	1.666	5.251	3.751	0.000	1.000	
0.15 mm	1.15	98	9.15	1.173	4.389	5.838	0.000	1.000	
0.075 mm	0.68	100	6.48	0.830	5.993	4.848	0.000	1.000	
Asphalt Cement Content (%)	0.18	100	6.08	0.250	2.300	2.500	0.000	1.000	
Relative Mat Density (%)	97.15	98.3	97.15	1.737	1.235	2.795	0.088	1.000	
Relative Joint Density (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no joint for lot.

Table E38
Lot 38 (3 sublots)

Material Characteristic	Current CEGS 02556		Modified CEGS 02556					
	MAD or Mean[1]	% Pay	Mean	Std. Dev.[2]	Q_L[3]	Q_U[3]	FN[4]	Pay Factor
Sieve Size (mea. units = % passing)								
19.0 mm	0.00	100	100.00	0.000	0.000	0.000	0.000	1.000
12.5 mm	1.53	100	90.27	2.113	3.676	3.424	0.000	1.000
9.5 mm	2.13	100	78.40	3.119	2.693	3.078	0.000	1.000
4.75 mm	6.27	90	58.73	2.608	1.048	5.853	0.138	1.000
2.36 mm	4.07	95	46.93	2.641	1.868	4.948	0.000	1.000
1.18 mm	1.60	100	34.03	1.943	3.878	5.388	0.000	1.000
0.60 mm	1.60	100	26.63	1.607	6.305	4.894	0.000	1.000
0.30 mm	1.37	100	17.53	1.361	6.268	4.750	0.000	1.000
0.15 mm	0.73	100	9.53	1.026	5.391	6.301	0.000	1.000
0.075 mm	0.83	100	6.63	0.862	5.954	4.485	0.000	1.000
Asphalt Cement Content (%)	0.40	95	5.83	0.404	0.825	2.144	0.247	0.772
Relative Mat Density (%)	96.24	80.6	96.24	0.600	2.072	9.673	0.000	1.000
Relative Joint Density (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

[1] Mean absolute deviation (MAD) for sieves and asphalt cement content; mean for relative mat density and relative joint density.
[2] Standard deviation.
[3] Q_L = lower quality index; Q_U = upper quality index.
[4] FN = total fraction nonconforming.
N/A - no joint for lot.

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12b.DISTRIBUTION CODE

13.ABSTRACT *(Maximum 200 words)*

This report documents the development of statistical acceptance procedures for asphalt pavement construction. These acceptance procedures are recommended as modifications to the current U.S. Army Corps of Engineers (USACE) Guide Specifications entitled "Asphaltic Bituminous Heavy-Duty Pavement (Central-Plant Hot Mix)." Technical reviews are provided for statistical specifications, including statistical acceptance plans. Current acceptance procedures for pavement construction that are used by Federal Government agencies are also reviewed. Recommendations for changes to the USACE Guide Specifications are presented in the form of an Engineering Technical Letter. Both the modified acceptance procedures and current acceptance procedures are applied to field data, providing comparisons in terms of lots rejected, lots accepted with full payment, and lots accepted with reduced payment.

14.SUBJECT TERMS
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